BpfJailer: eBPF Mandatory Access Control

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Agenda

01 Jailing Cases

02 Architecture and Deployment

03 Process Tracking and Enrollment

04 Path Matching with eBPF

05 Challenges of Root User Jailing

06 Signed Binaries with eBPF

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Overview

- Created to sandbox/jail untrusted workloads
  - Jailing: Reducing privilege for low-trust processes
- Has become a popular tool for security orgs
- Now covers system-wide MAC including both restricted and privileged roles
- Tracks processes using a task_storage map, copied to children on clone()
  - Original process is enrolled in various ways
- Deployed across most on infra in socket activated mode, key surfaces in an always-on mode and/or baked into init
  - Working to eliminate socket activation

Plan to open source key components (eBPF and eBPF loading code) in 2026

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Why Create a New MAC Solution

- SELinux: slow
  - Completely eliminated at Meta
- AppArmor: didn’t have all required features, path based exclusively
- Landlock: didn’t have all required features, processes always need to enroll themselves with API

- BpfJailer can operate in both a path based (involuntary), and non path based mode (voluntary)
- Covers full range of features, including features not present in other MAC solutions
  - Signed binaries
  - Proxying/Protocol interception
- eBPF implementation allows development to move quickly and safely without changing upstream
- No measurable performance regressions across any workload/host type

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Some Use Cases

- **Original:** Sandboxing VMs running untrusted (AI generated) code
  - Extremely low privilege
- Restricting access to Trusted Execution Environment (AMD SEV-SNP) devices
  - Needs to defend against potentially root level insiders
- Restricting access to database files
  - Needs to defend against root level insiders (less stringent)
- Jailing AI agents
  - Needs to allow most development actions
  - Needs to support legacy code that doesn’t expect to be restricted
- Restricting access to certificates on development servers
  - Needs to allow a permissive environment overall (including root)

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Complete

Planned

Capabilities

Networking

- TCP bind()
- TCP connect()
- UDP sendmsg()
- UDP recvmsg()
- Unix domain bind()
- Unix domain connect()
- Unix domain sendmsg()
- Vsock bind()
- Vsock connect()
- accept()
- DNS
- DBus
- TCP and UDP Proxy
- CA injection and local TLS interception

Execution

- Exec binary and arguments
- setuid/gid flags

Filesystem

- File path matching
- mount()
- Restricted devices

IPC

- SysV
- Posix

Kernel

- Kernel modules
- eBpf programs and maps

Permissions

- setuid()/setgid()
- Capability changes

Tampering

- ptrace()
- process_vm_readv()/writev()
- /proc

Other

- Signed binaries
- ioctl()

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In This Talk

- Only going to go in depth on the deployments and the more complex features
  - Path matching
    - Used for filesystem, unix socket, and exec restrictions
    - Used for binary path and cgroup enrollment
  - Signature validation

- Networking and other restrictions are simpler and have more mundane solutions
  - Don’t need any support from the broader community here

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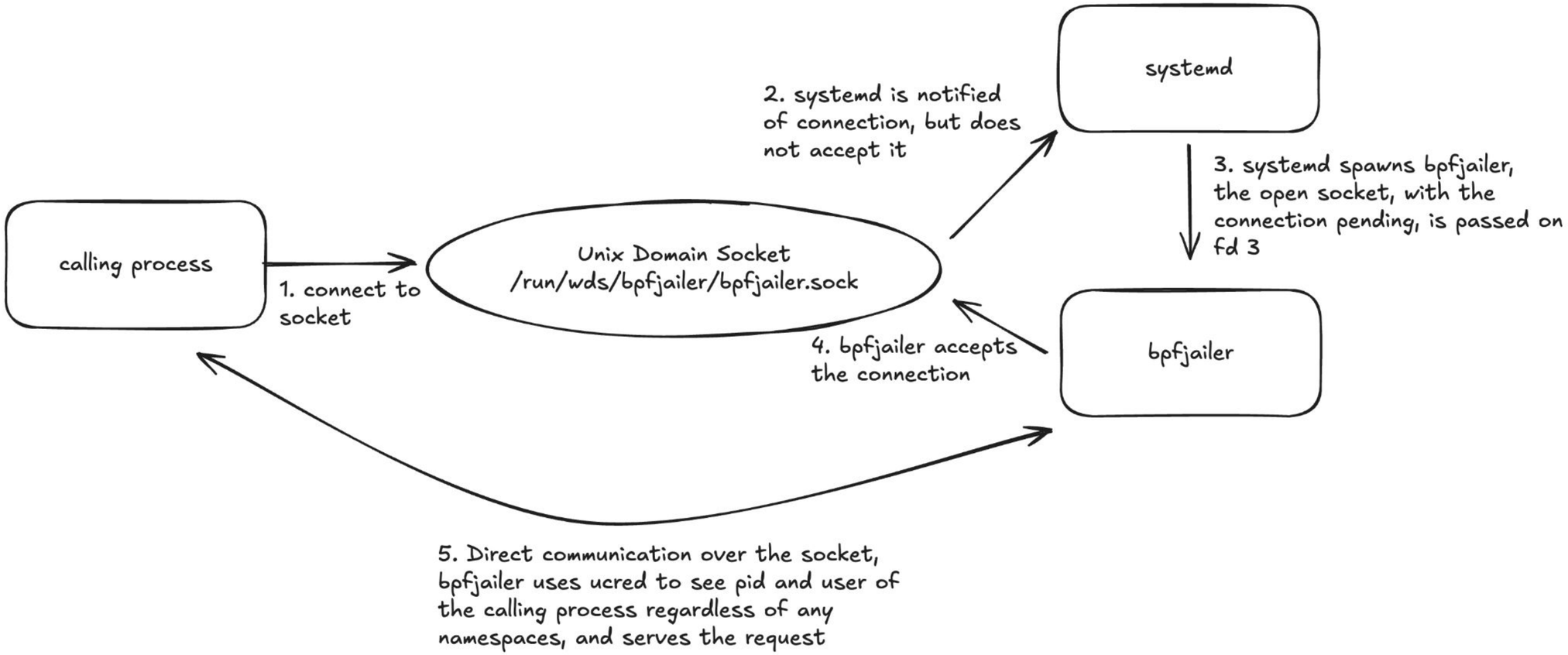
Socket Activation



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More Enrollment Options

- Unix socket enrollment is directly included in Meta's container scheduler (tupperware)
- Can inject mount namespaces and symlinks as part of jailing
- We found this method to be too brittle and introduce friction/latency for some applications
  - Sometimes difficult/impossible to force open-source/legacy code to utilize BpfJailer API
- Added several other options:
  - Executable Path
  - Cgroup Path
  - Xattr on executable
- BpfJailer has more or less outgrown socket activation as it has been deployed more widely, and now is usually deployed as a normal systemd service or as part of init (covered later)

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Roles

- Each pod (unit of tracked processes) is mapped to a role (set of policy)
- BpfJailer supports stacked pods, pods within pods
- Currently allows up to 4 layers of stacking
- Roles are evaluated cumulatively allowing different levels of isolation or exemptions for certain processes
- Examples:
  - Container receives one policy, workload inside container receives more restrictive policy
  - Container receives one policy, specific process in init receives exception to policy
  - Devserver users receive one policy and agents receive a second, stacked policy

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Init (Daemonless) Installation

- Using a daemon to manage eBPF programs opens a gateway to attack
- For some applications (eventually all) BpfJailer is baked into the init system
  - Bootstrap binary pins eBPF programs and maps then dies before switch to rootfs
  - Programs cannot be removed or upgraded without reboot
- Logging daemon (installed later) has access to ringbuffers for logging access events and errors
  - Would be nice to eliminate this in favor of eBPF networking helpers that have been proposed
    - Would solve cross binary versioning issues
- All other access to BpfJailer eBPF programs and maps is blocked
- Can’t enroll processes via socket, needs to use other methods

We will work to open source this stack in 2026

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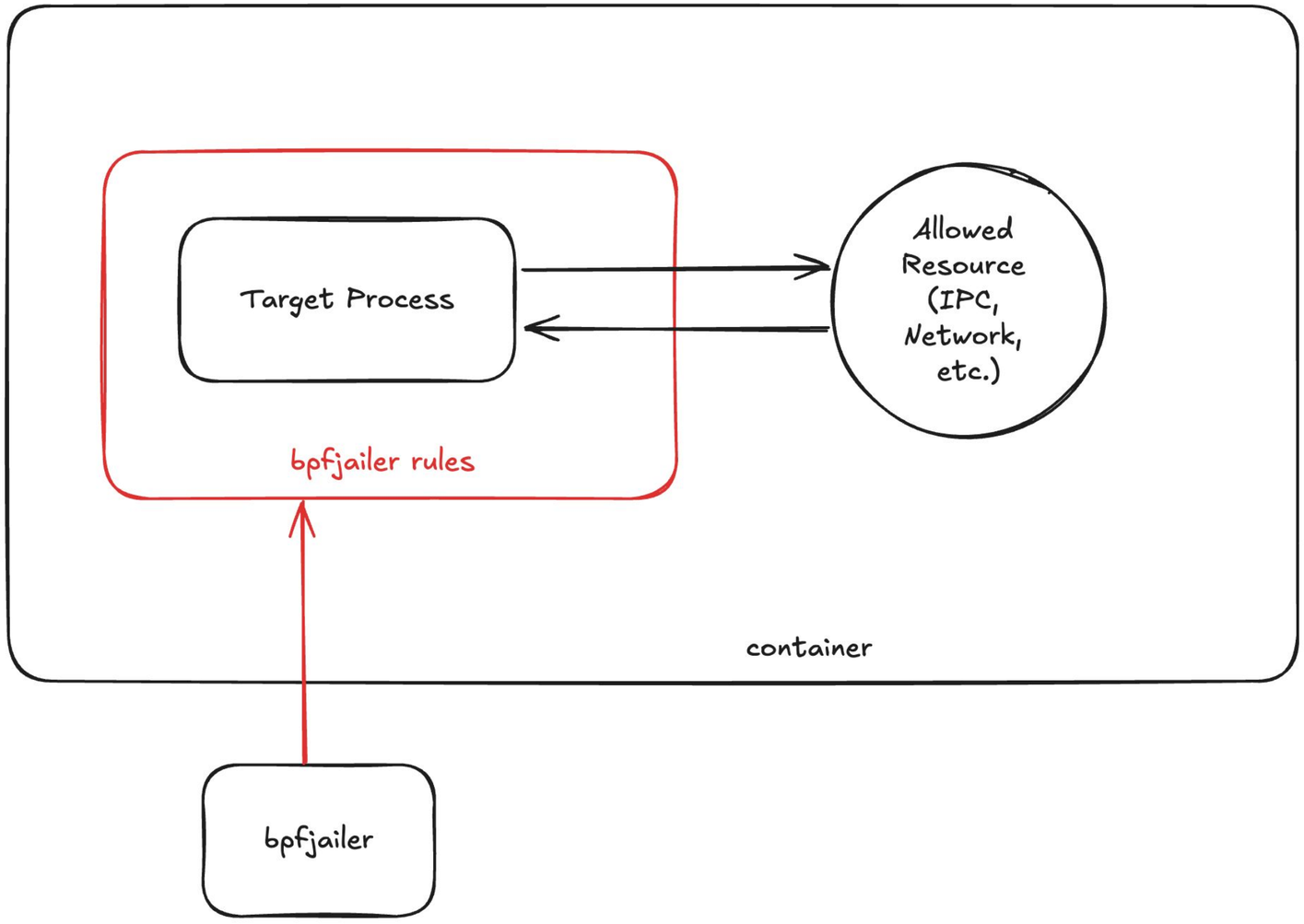
Jailing

- Specific processes are jailed
- Allows extremely locked down policy
  - Individual IPC and network resources are allowlisted
- Jailing entire containers is also supported
- BpfJailer service can support 10,000 simultaneous pods (jails)
  - Number of tracked processes unbounded



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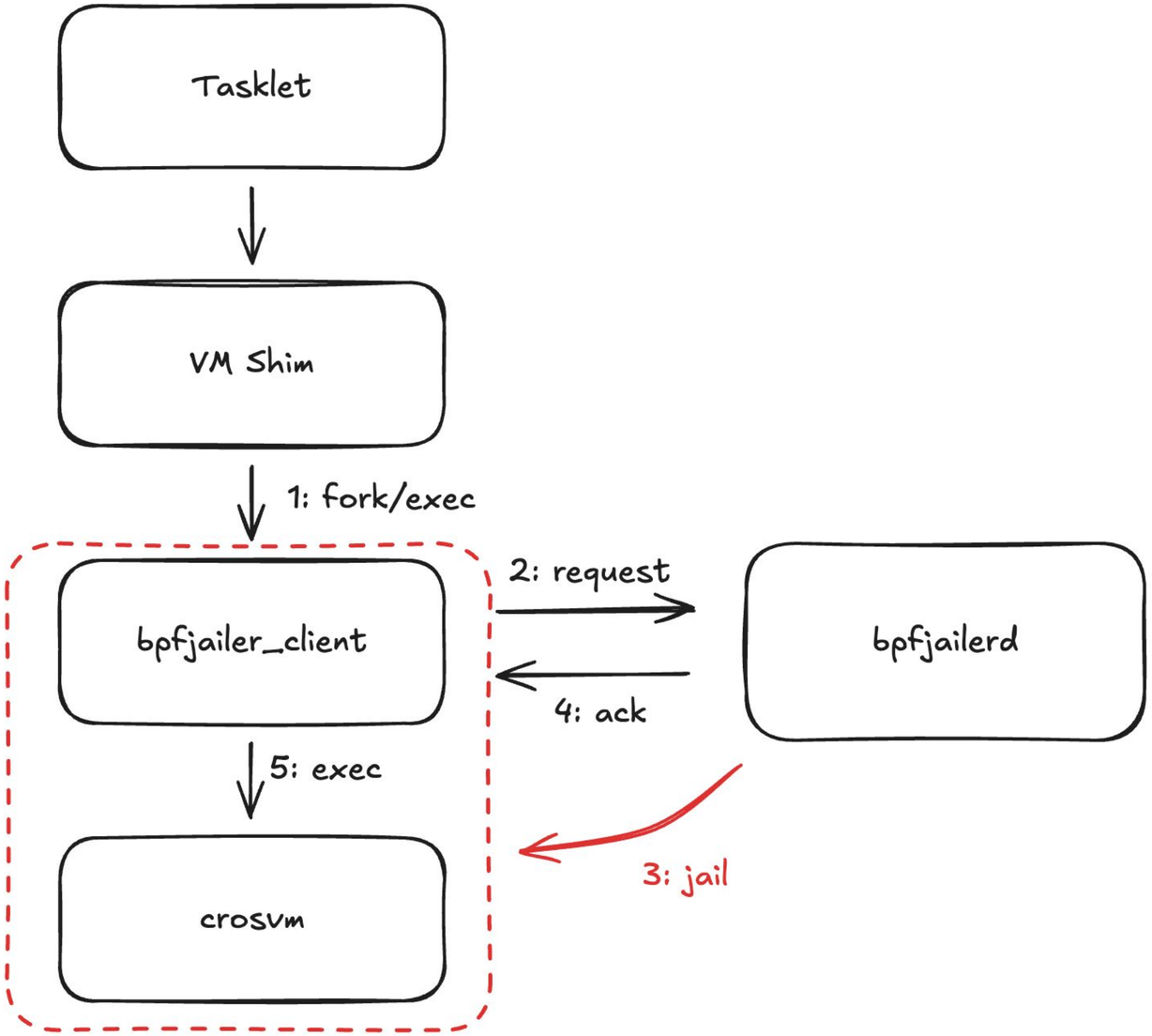
Example: VM Jailing

- VM shim controls crosvm lifetime
- Forks into bpfjailer_client which jails itself then enters crosvm
- Jailing is in the path of execution which enforces jailing of crosvm and children processes
- Drawback is that BpfJailer downtime can block crosvm from spawning
  - Systemd orchestration and container orchestration not synchronized



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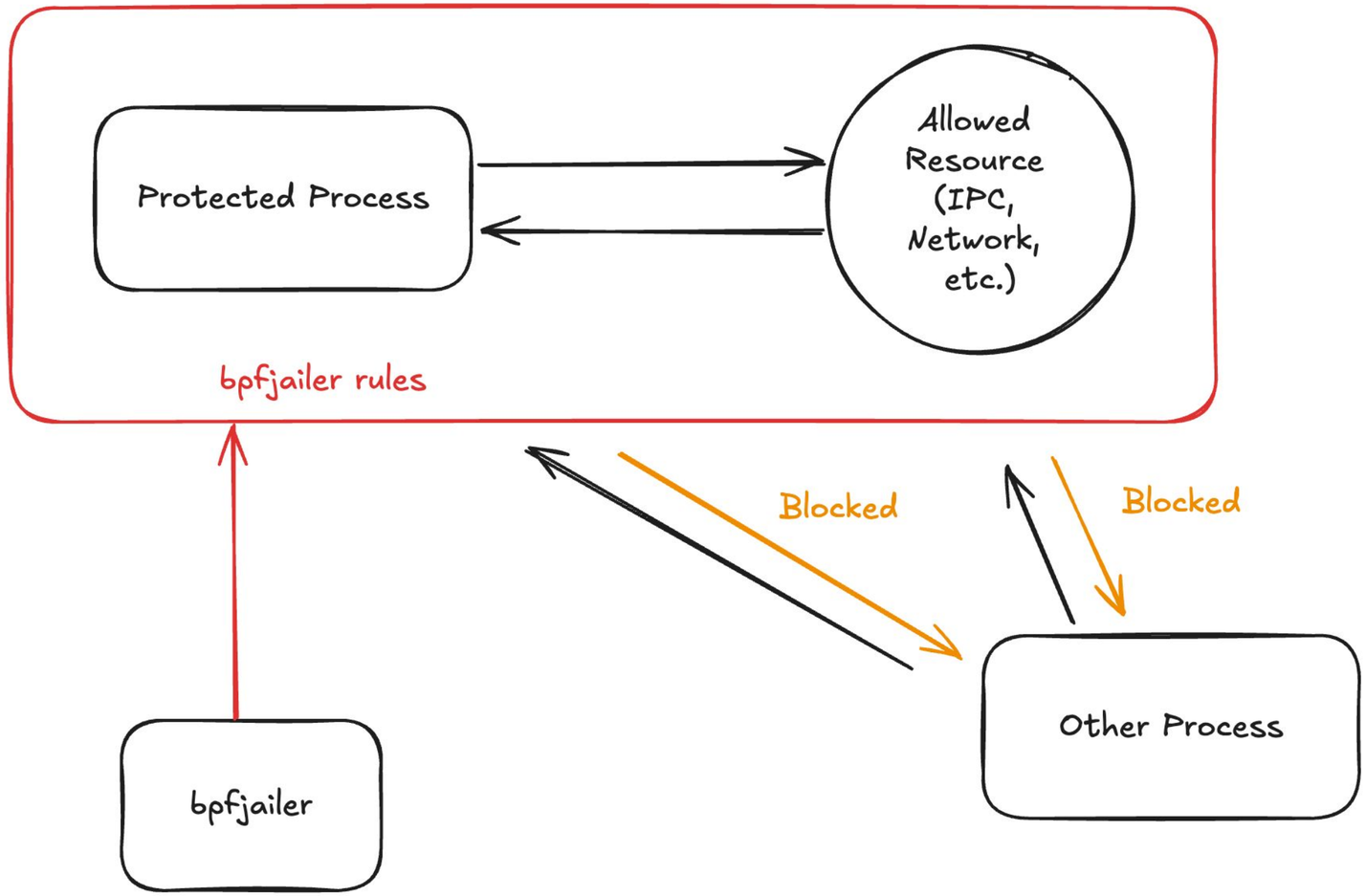
Access Control

- Can also function in reverse, protecting certain processes, blocking external access
  - kill()
  - ptrace()
  - /proc
  - Binary tampering
- The protected process is the only one allowed to access the protected resource



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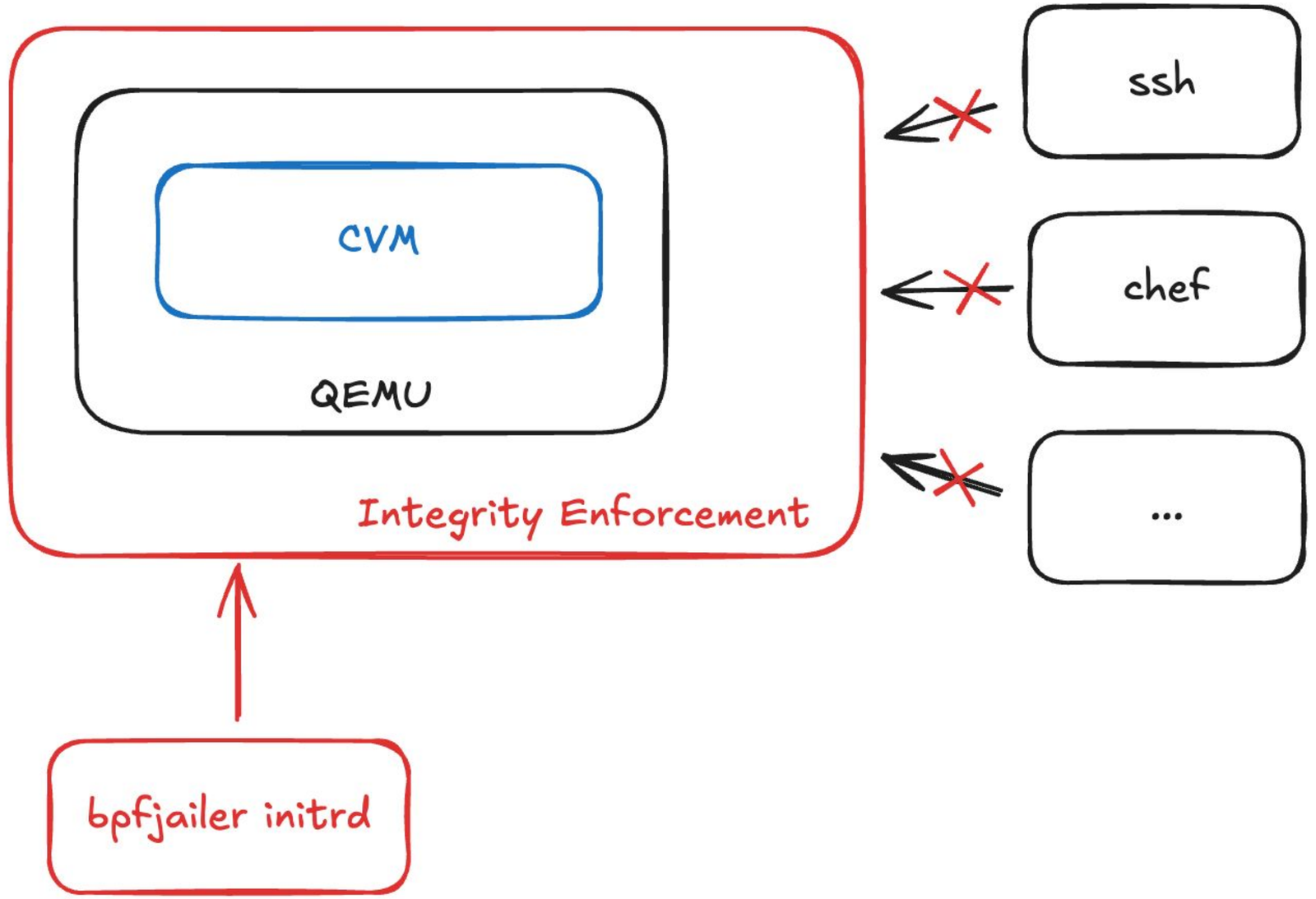
Example: WhatsApp TEE

- Need to protect CVM and QEMU from tampering
- Signed binaries
- Ptrace and /proc blocked to protected processes
- Kernel modules restricted

Rules installed by initrd and immutable + measured as part of attestation



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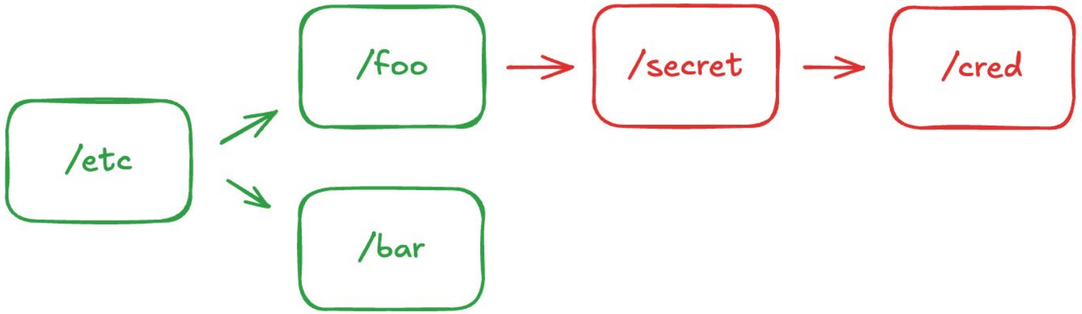
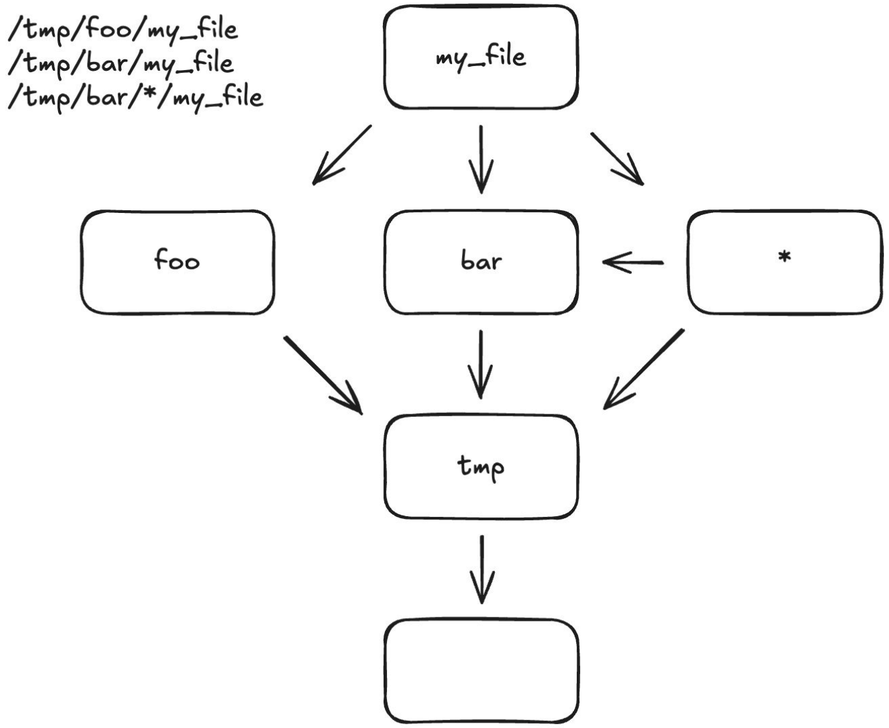
Path Matching



- Path based (what users expect)
  - Supports hierarchical structures of directory based permissions
- Walks dentry/mount tree in order to match each open()/rename()/etc.
- Constructs a graph/state machine built out of hash maps and array maps (originally kernel 6.4+, now 6.9+). Supports:
  - Wildcarding (for example, need to ignore ids in container paths)
  - More efficient use of CPU/RAM then hashing whole path at once
  - Corpus of thousands of patterns
- Cache inodes and invalidate on rename and mount lock changes



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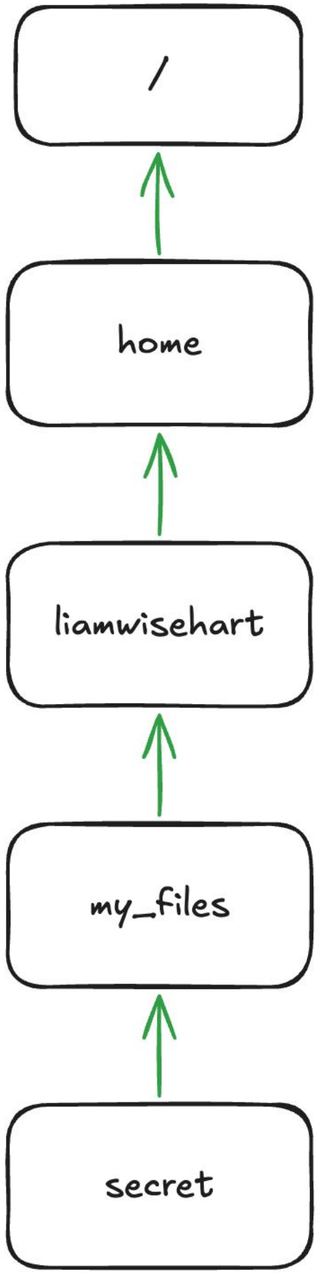
Extract Vector of String Views

- Two step process, construct vector of string views, then try to match
  - Takes 2,000 lines of eBPF code and runs up against stack limit, instruction limit, etc.
  - Required significant work against the verifier
- Constructs a vector of string views (d_name) up to 255 directories deep of up to 255 byte names
- Can’t filter bind mounts due to the limitations of securty_sb_mount
  - Doesn’t expose bind mount path in dentry form (vulnerable to symlink based attack)
  - Hard links and renames can just be blocked with existing LSM hooks



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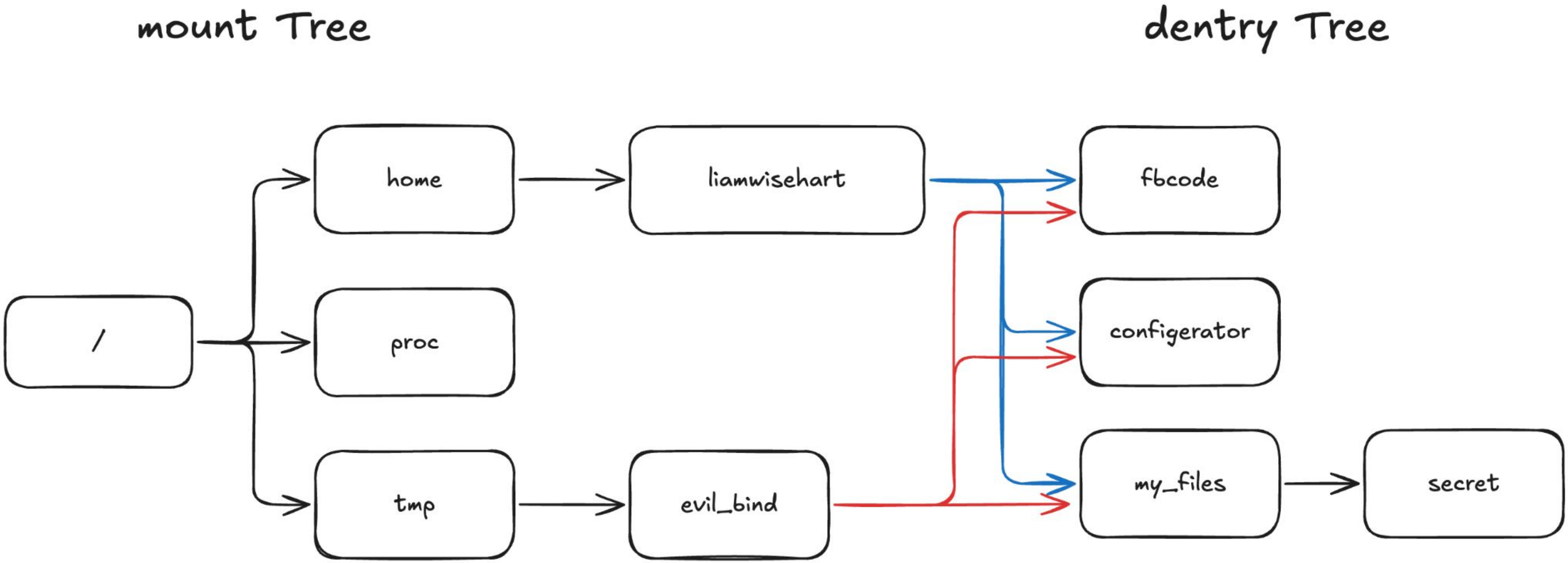
Path Matching: Bind Mounts Create Alternate Paths



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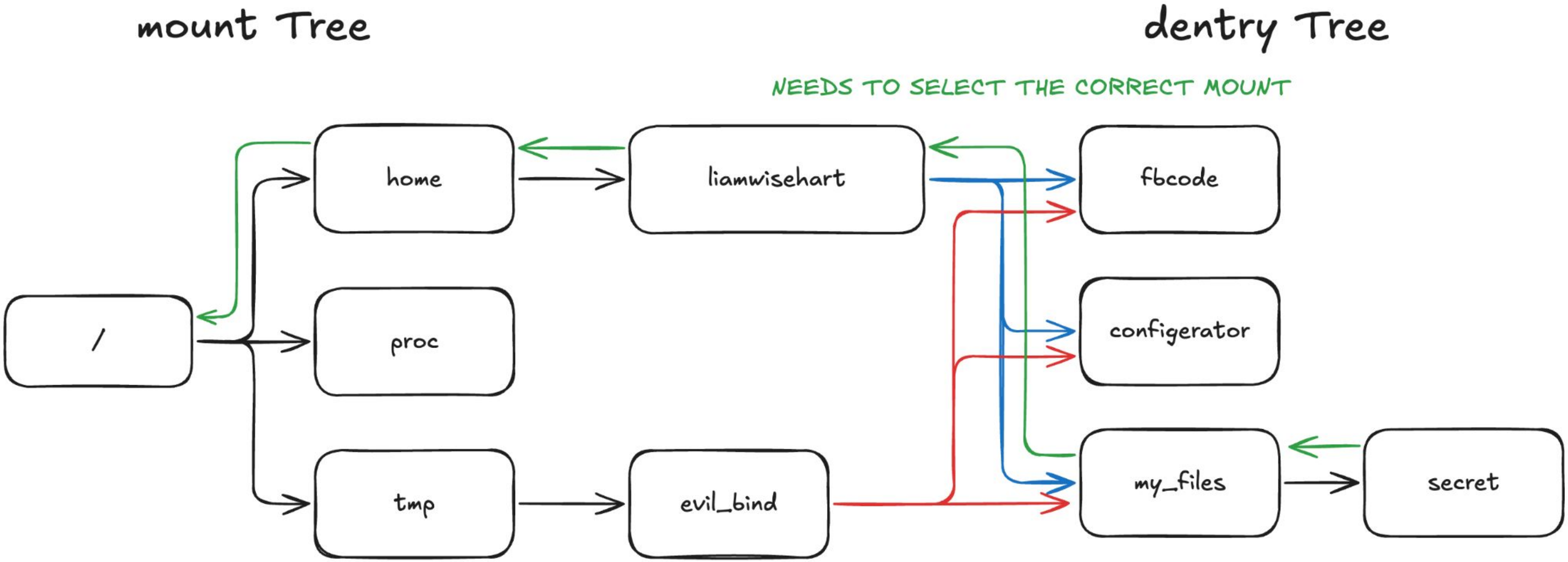
Path Matching: Need To Walk Mount Tree Correctly



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Mount Traversal

- Traversal algorithm:
  - Enumerate all mounts in the **root (pid 1)** mount namespace (cached based on mount lock)
  - Build a map of mount root dentry -> struct mount
  - For each dentry select the **oldest** mount (lowest mnt_id_unique)
  - Attempt to resolve a path, by walking dentries/mounts, up to the root dentry of the root mount namespace
  - If we can't find the root this is not a tracked file/directory (likely isolated to a different mount namespace), otherwise try to match
- Use LSM to protect against mount/unmount and renaming directories on the paths as well as hard links

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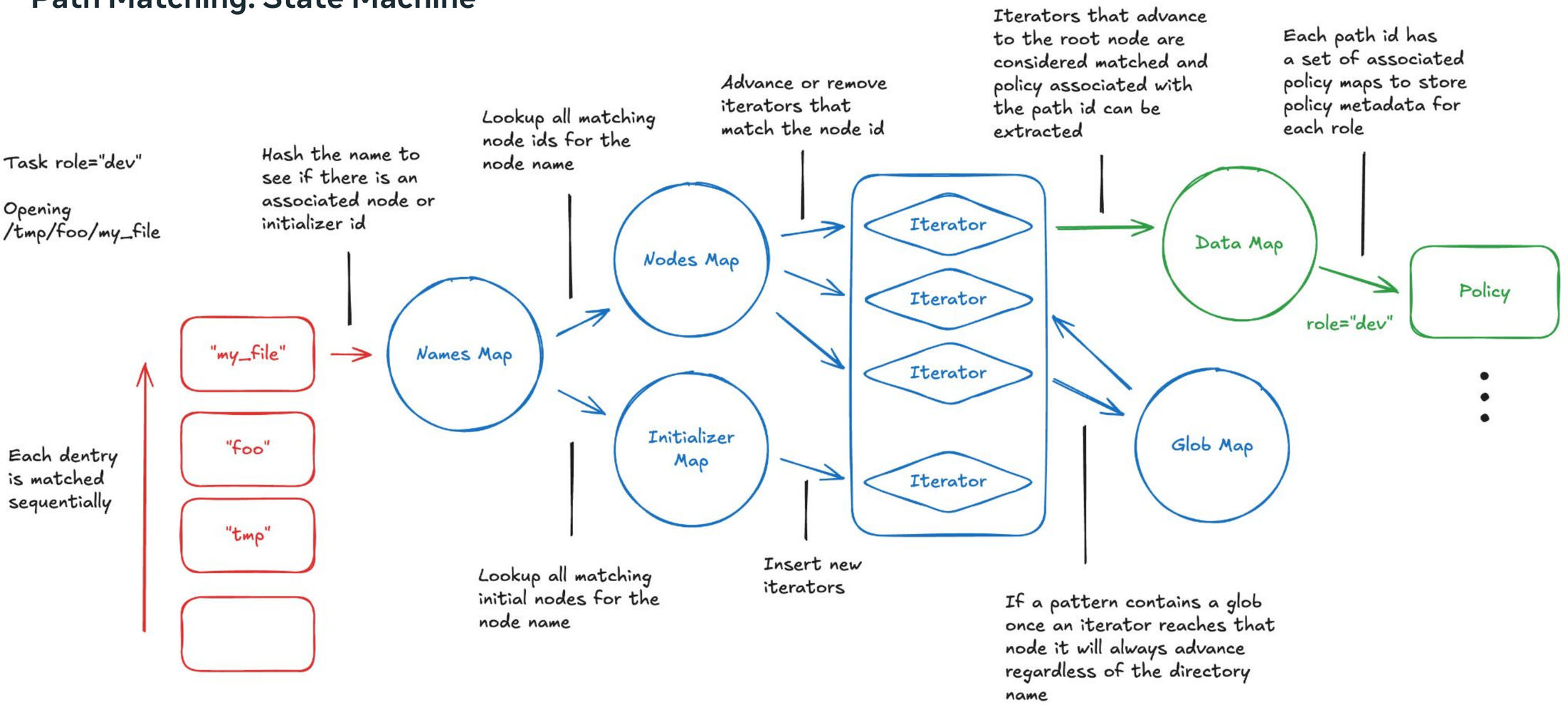
Path Matching: State Machine



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Key Issues

- Filesystem matching is very difficult, and requires hacks to get around verifier limits
  - Matching is significantly slower than other LSM operations – though no measurable regressions have been observed, even in IO heavy workloads (compiling, database tiers)
- Need to match capabilities of LKM/user space security products which do not have eBPF limitations
- Policy can become very complex to cover all possible attacks (rename, remounting, etc.)

- Need to simulate the environment large amounts of legacy code expects
  - Need to inject certificates and other files into jailed (agentic) processes
  - Currently uses a mount namespace and bind mounts

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Possible New Kernel Feature: open() Redirection

- Can we redirect the open syscall (and friends) similar to how connect and sendmsg can be redirected
- Would effectively allow eBPF to force a process into a mount namespace
  - Putting a shim into a process's startup/orchestrator can be significantly more difficult then just identifying it with eBPF based on some criteria
  - The issue here is that enrolling legacy code into mount namespaces can be difficult
  - In addition, jailed agents still have broad privileges and can learn (or be taught) to escape namespaces
- Would give security daemons more options then a binary block/allow
- Would require several new helpers and new hooks

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What Guarantees can we Make About A Host with Malicious Root Users

- Had some lofty goals that had to be stripped down to essentials due to the difficulties of trying to restrict root users
- In the end for certain (eventually all) workloads
  - BpfJailer is placed in initrd, clients will not connect to hosts unless init and lower level boot artifacts pass hash test
    - **Guarantee: BpfJailer was started on the host**
  - BpfJailer defends its pinned programs and maps against tampering, blocks LKM loading
    - **Guarantee: BpfJailer is still running**
  - Key resources are restricted only to a single role
    - **Guarantee: Unauthorized access to key resource only is blocked**
  - Service accessing key resource have signed binaries, vetted command-line arguments, signed config files, and is protected from tampering (ptrace and friends)
    - **Guarantee: Key resource is only accessed by expected service**

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Signed Binaries

- x509 certs are loaded into child of root keyring at startup (packaged into init if BpfJailer is put there)
  - BpfJailer protects access to its keyring
- Binary validation:
  - Fsverity hash signed, signature included in xattr on binary and all shared objects needed
  - When a binary executes into a role that requires signing BpfJailer validates the signatures
    - Validation occurs on mmap_file if the file is in exec mode
- Currently used for QEMU when used in TEE to block unauthorized access to kvm and AMD SEV-SNP interfaces
  - VM image is verified by client
- Command line arguments will be vetted in 2026
- Config files and other artifacts will be signed in 2026

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Future Work

- Continuing to iterate on filesystem path matching (regex)
- Easy to configure profiles for users who don’t understand eBPF
- Enrolling more of the Meta fleet in these features
- Migrating into a daemonless/initrd model fleetwide
- Open source

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