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Trusted Systems Virtual Institute

Predictable and Scalable Remote Attestation

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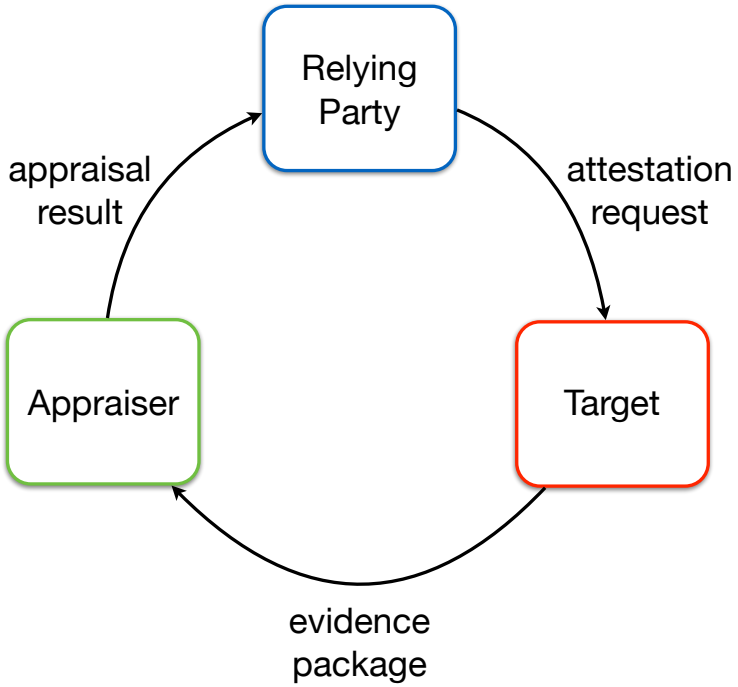
Predictable and Scalable Remote Attestation

- Evidence and Time - A semantics of evidence over time that allows predictions about the effectiveness of attestation evidence in appraising systems
- Flexible Mechanisms at Scale - A semantics for appraisal architectures and its realization as a collection of reusable attestation components and tools for static analysis.
- Empirical Case Studies - Large scale empirical studies of defining, implementing, and running attestation architectures with applications in supply chain and zero trust.

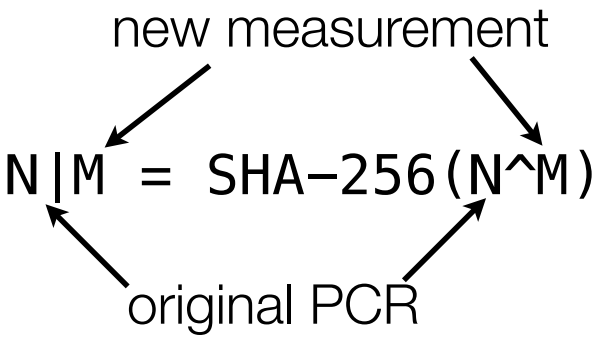
Semantic Remote Attestation

- Relying Party requests appraisal
  - specifies needed information
  - provides a fresh nonce
- Target gathers and generates evidence
  - measures OS & applications
  - generates cryptographic signatures
- Appraiser assesses evidence
  - good application behavior
  - infrastructure trustworthiness
  - good nonce



Extending a PCR

- PCRs contain measurements
  - SHA-256 hashes of images and data
  - may be more sophisticated
- PCRs are extended rather than set
  - SHA-256 of the PCR concatenated with a new measurement
  - captures the new value, original value, and order
- Records the state of a system and trajectory of states
  - used in attestation to evaluate system state
  - used to seal secrets to system state

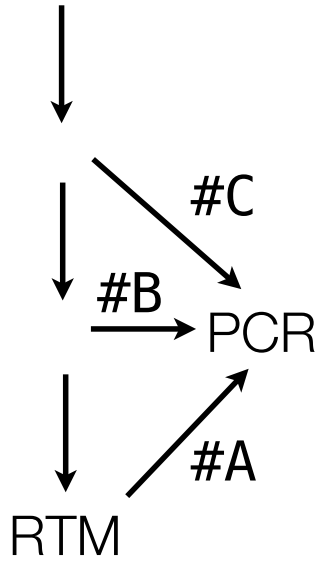


order matters!

$N|M \neq M|N$

Measurement to Record Boot Trajectory

- SENTER resets the TPM
  - PCRs initialize to **#FFFF**
  - SENTER resets PCRs to **#0000**
- RTM measures and starts A
  - measures A
  - extends PCR with #A
  - starts A
- A measures and starts B
  - measures B
  - extends PCR with #B
  - starts B
- B measures and starts C
  - measures C
  - extends PCR with #C
  - starts C
- C is running with PCR indicating startup status
  - record of what binaries started
  - record of startup order
  - *TPM can seal secrets to the PCR value*



PCR:=0|#A|#B|#C

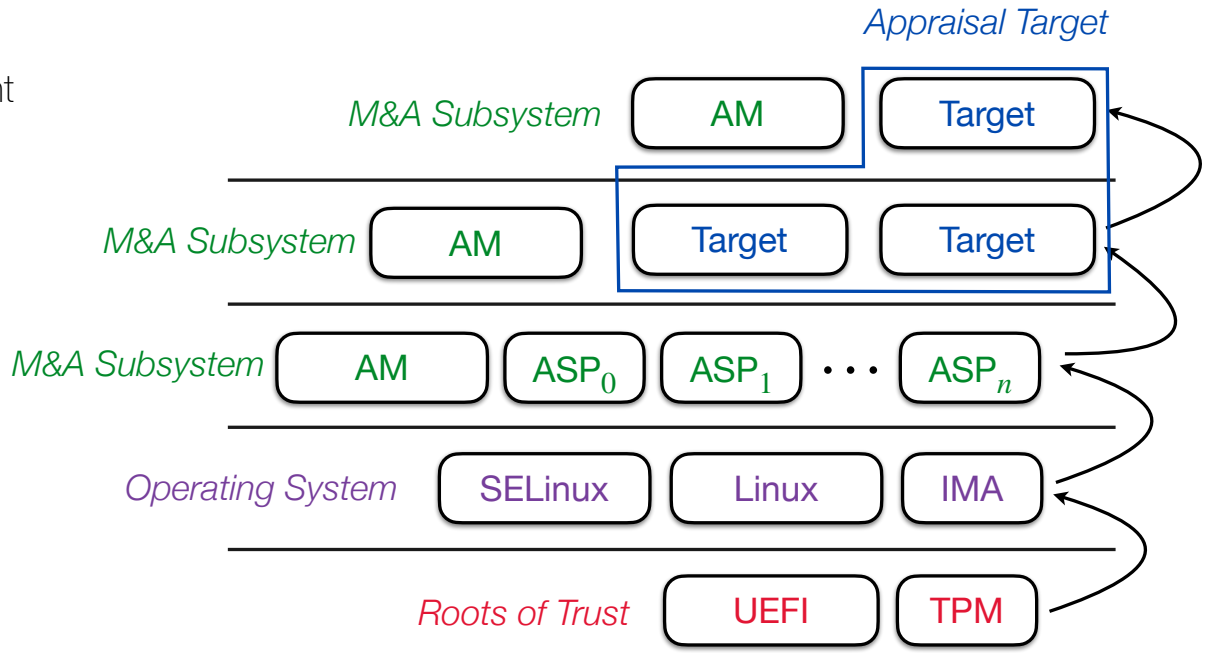
PCR:=0|#A|#B

PCR:=0|#A

PCR:=0

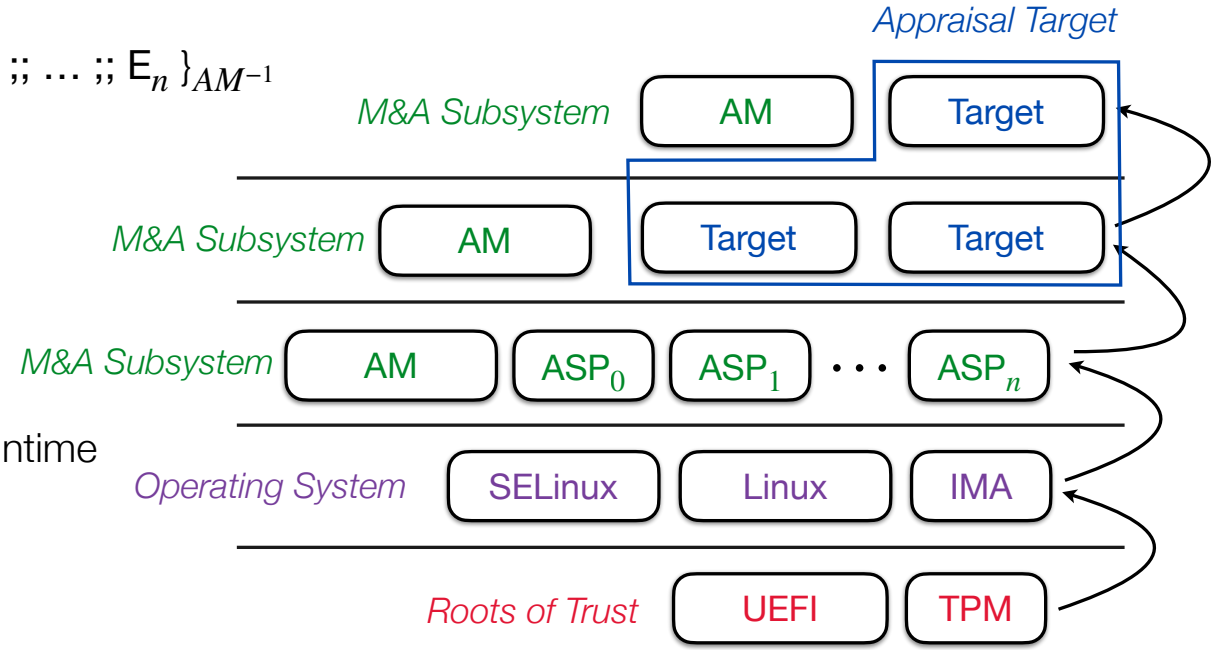
Layered Runtime Attestation

- Target
  - system to be appraised at runtime
  - potentially with component targets
  - cross domain system for this experiment
- M&A Subsystem
  - MAESTRO attestation manager (AM)
  - unique attestation manager key (AM^{-1})
  - attestation service providers (ASPs)
  - Copland attestation protocol
- Operating System
  - RedHat Linux
  - SELinux
  - IMA
- Roots of Trust
  - storage and reporting (TPM)
  - measurement (UEFI)



Layered Runtime Attestation

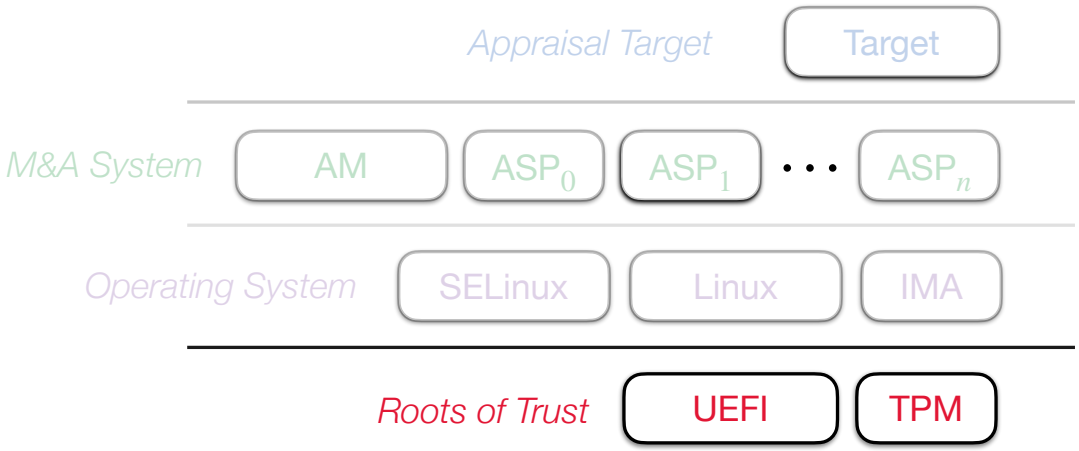
- $\{ E_0 ;; \{ E_{10} ;; \{ E_{20} \}_{AM^{-1}} ;; \ldots ;; E_{1n} \}_{AM^{-1}} ;; \ldots ;; E_n \}_{AM^{-1}}$
  - E_k - evidence from ASP execution
  - ;; - bundling operator from protocol indicating order
  - $\{\ldots\}_{AM^{-1}}$ - Attestation Manager signature
- Layering results in nested evidence
  - ASP invokes an attestation manager - @AM[…]
  - AM produces a signed evidence package
  - MAESTRO enables arbitrary nesting
- AM^{-1} signing key indicates transition to runtime
  - signing memorializes good boot
  - keys must be unique
  - only an AM can access its key
  - access allowed only on good AM startup



proper bundling
∧ satisfies appraisal policy
∧ valid signatures
} ⇒ trustworthy target

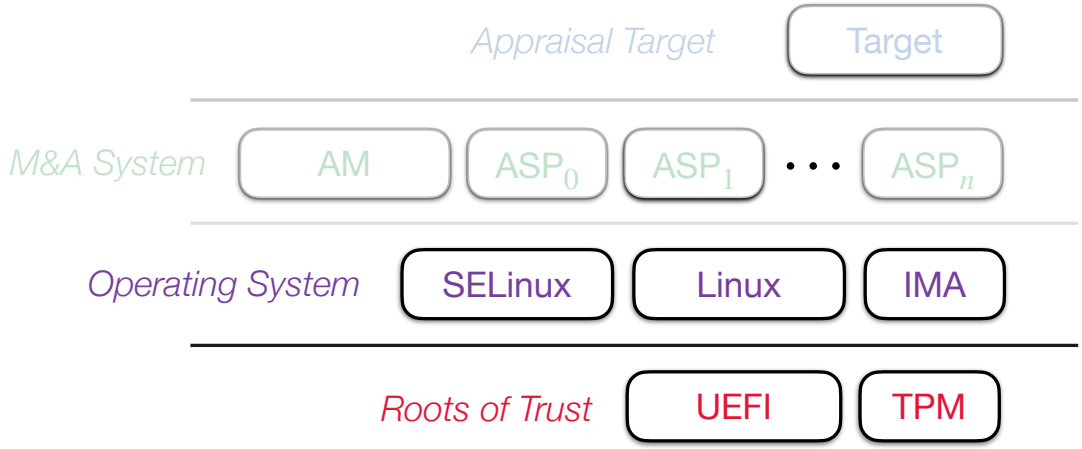
Roots of Trust Base

- TPM
  - Root of trust for Storage and Reporting
  - trusted *a priori*
  - evidence signing
  - generates, stores and seals AM's signing key
  - binds signing key to an AM
- UEFI
  - Root of trust for Measurement
  - trusted *a priori*
  - bootloader measurement and initiation



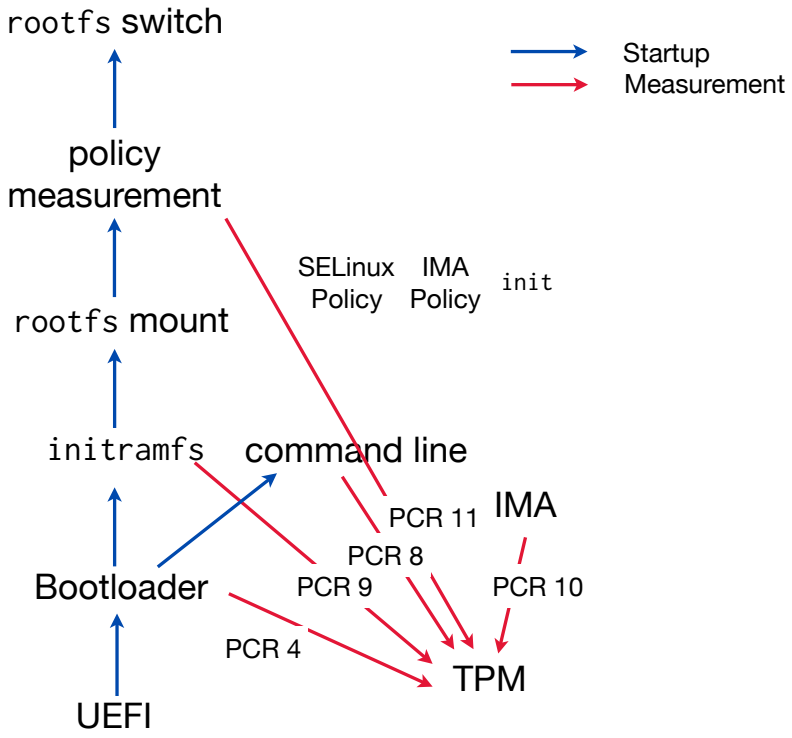
Operating System Layer

- Measure and start Linux
- Measure policy and start SELinux
- Measure policy and start IMA



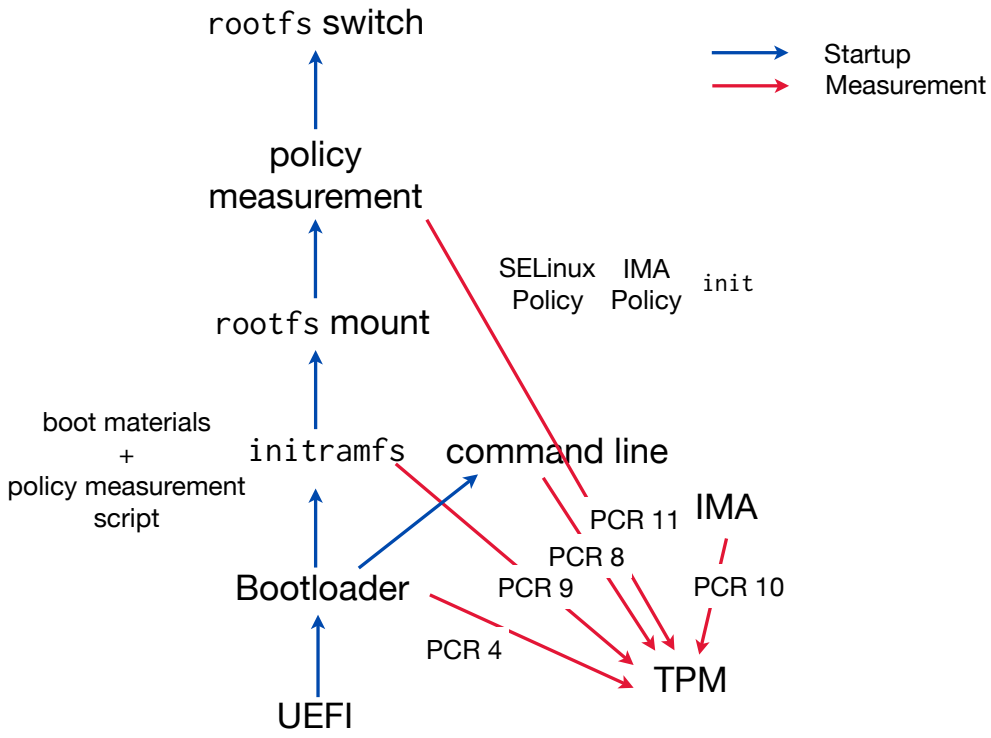
Trusted OS Infrastructure

- Firmware measures and starts boot loader
  - firmware hashes and starts boot loader (PCR 4)
- `initramfs` contents
  - traditional boot materials
  - custom measurement script for SELinux and IMA policies and `init` system
  - IMA will use SELinux types requiring early policy measurement and SELinux start
- Boot `initramfs`
  - bootloader hashes command line to start `initramfs` (PCR 8)
  - bootloader hashes and starts `initramfs` (PCR 9)
- Switch to `rootfs`
  - mount `rootfs`
  - hash IMA and SELinux policies (PCR 11)
  - hash `init` binary
  - execute `init` binary on `rootfs`
  - kernel running with measured IMA and SELinux policies



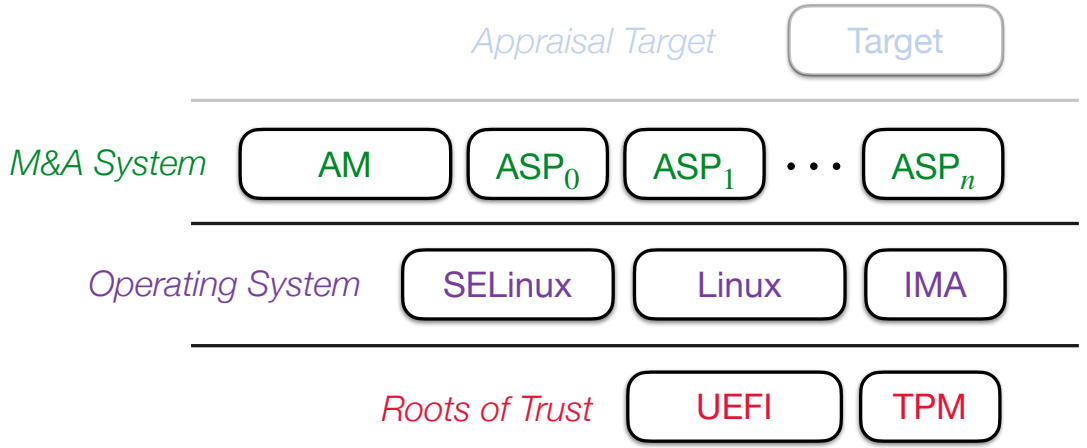
TPM State

- Good PCR 4
  - good bootloader
  - should measure `initramfs`
  - should use command line specification to start
- Good PCR 8 & 9
  - good command line starts `initramfs`
  - good `initramfs`
  - good boot materials
  - *good policy measurement script*
  - *good measurement script invocation*
- PCR 10 (ignored here)
  - memorializes IMA trace
  - not useful for sealing
- Good PCR 11
  - policy measurement ran
  - good initial SELinux and IMA policies
  - good `init` indicates start with good policies



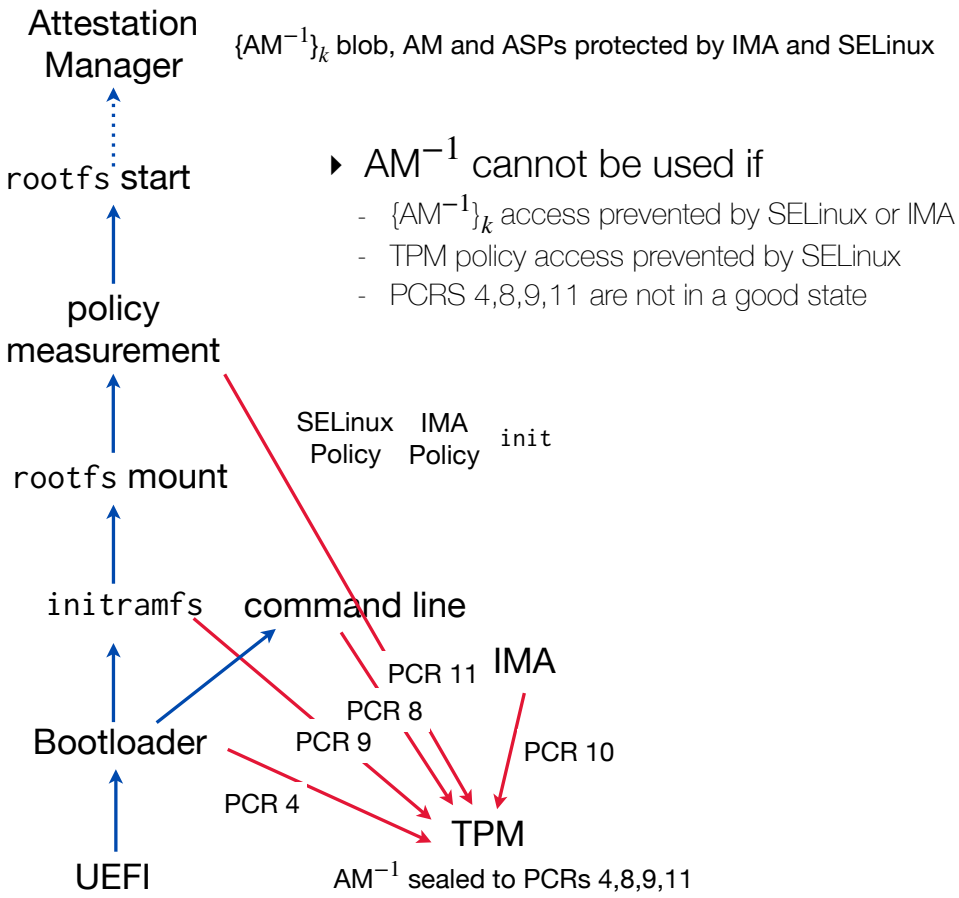
Runtime Attestation Layer

- Measure and start AM
- Establish ASP libraries
- Ensure AM^{-1} availability
- Begin Copland protocol execution



AM^{-1} Protection and Use

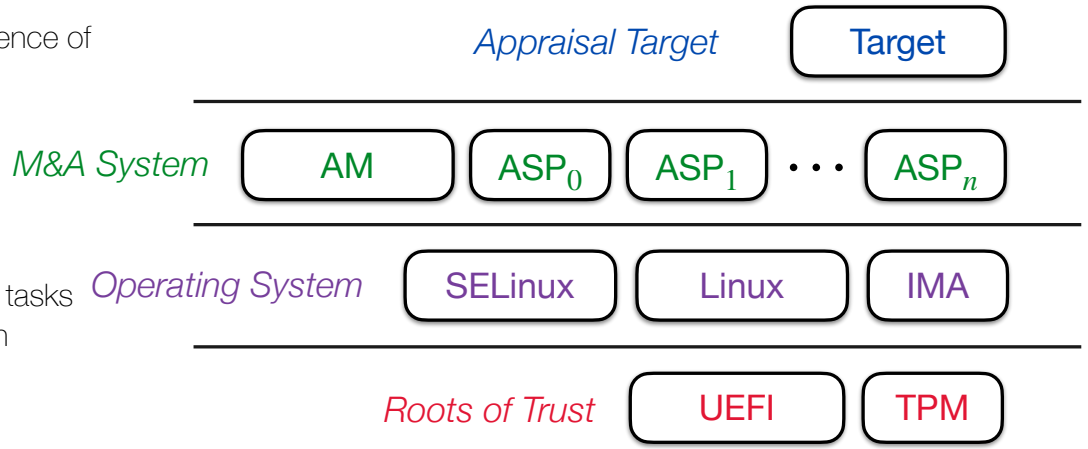
- Starting and Protecting AM
  - IMA policy prevents bad AM binary starting
  - IMA policy prevents bad ASPs from running
  - SELinux provides runtime access control
  - AM is formally verified to properly execute Copland protocols
- Generating and Protecting AM^{-1}
  - TPM generates AM^{-1} from $\{AM^{-1}\}_k$ blob on demand
  - SELinux enforces $\{AM^{-1}\}_k$ access control
  - IMA Extended Verification Mode (EVM) protects $\{AM^{-1}\}_k$ permissions
  - Authorized TPM policy must be loaded to enable key
  - Authorized TPM Policy seals AM^{-1} to PCRs 4,8,9,11
  - SELinux enforces access control over TPM Policy
- Using AM^{-1}
  - key is a strongly bound identifier for the AM
  - AM signature binds evidence to the associated AM
  - AM signature memorializes boot
  - effectively extends trust to user-space attestation mechanisms



- AM^{-1} cannot be used if
  - $\{AM^{-1}\}_k$ access prevented by SELinux or IMA
  - TPM policy access prevented by SELinux
  - PCRS 4,8,9,11 are not in a good state

General Purpose Runtime Attestation

- Boot to AM is generic
  - any good signature over evidence $\forall e \,.\, \{e\}_{AM^{-1}}$ is evidence of trusted AM
  - AM is configurable and formally verified
  - small and memory safe
- M&A Subsystem
  - runs arbitrary Copland attestation protocols
  - attestation service providers (ASPs) perform attestation tasks
  - Copland attestation protocols sequence ASP execution
  - AM signing itself is an ASP
- Appraisal Targets
  - customize ASPs and protocol for specific applications
  - no requirement to customize target
- Evidence $\{ \mathsf{E} \}_{AM^{-1}}$
  - check signature to assure evidence integrity and good boot
  - check evidence to establish trust in target
  - formal semantics for protocol and evidence



proper bundling
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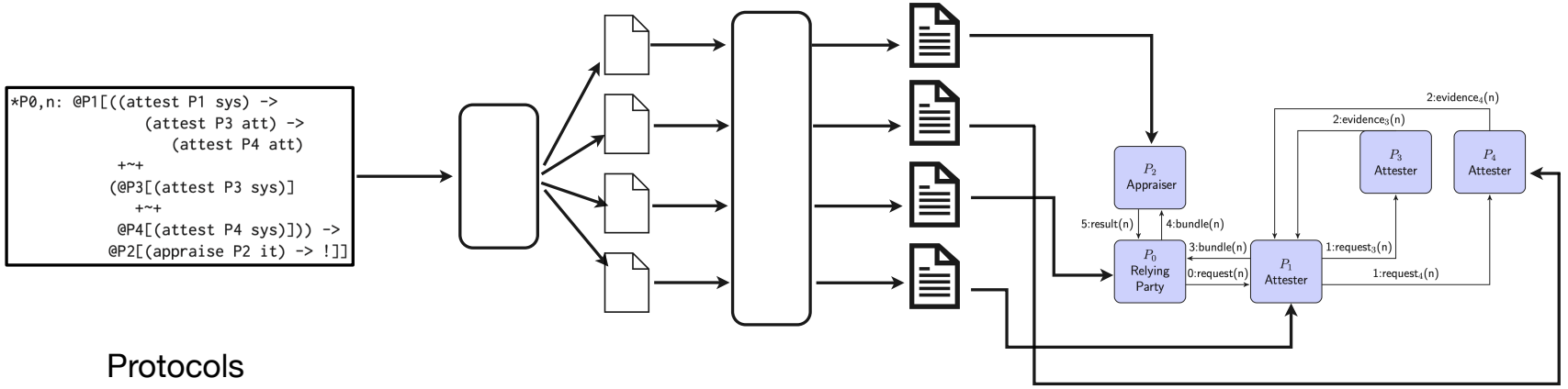
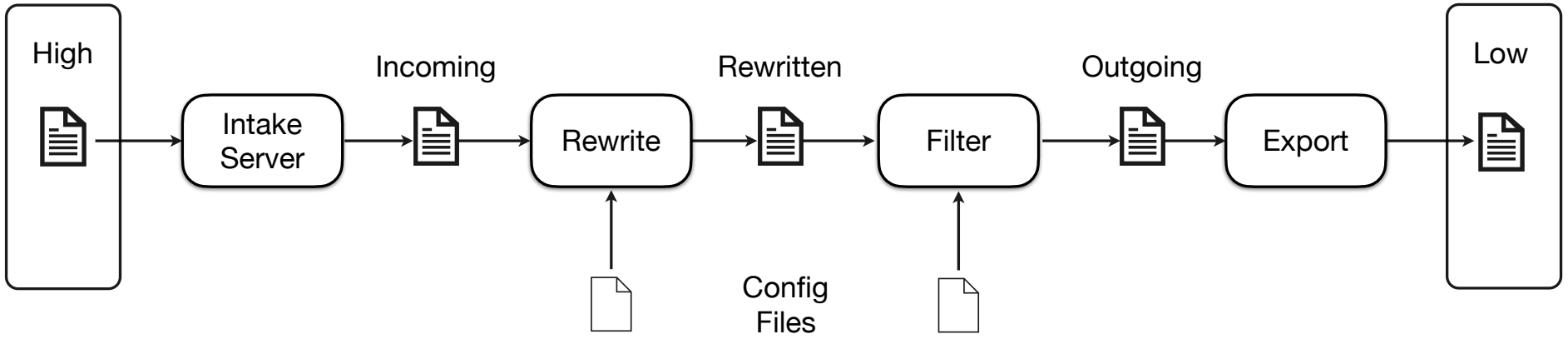
MAESTRO Attestation Infrastructure



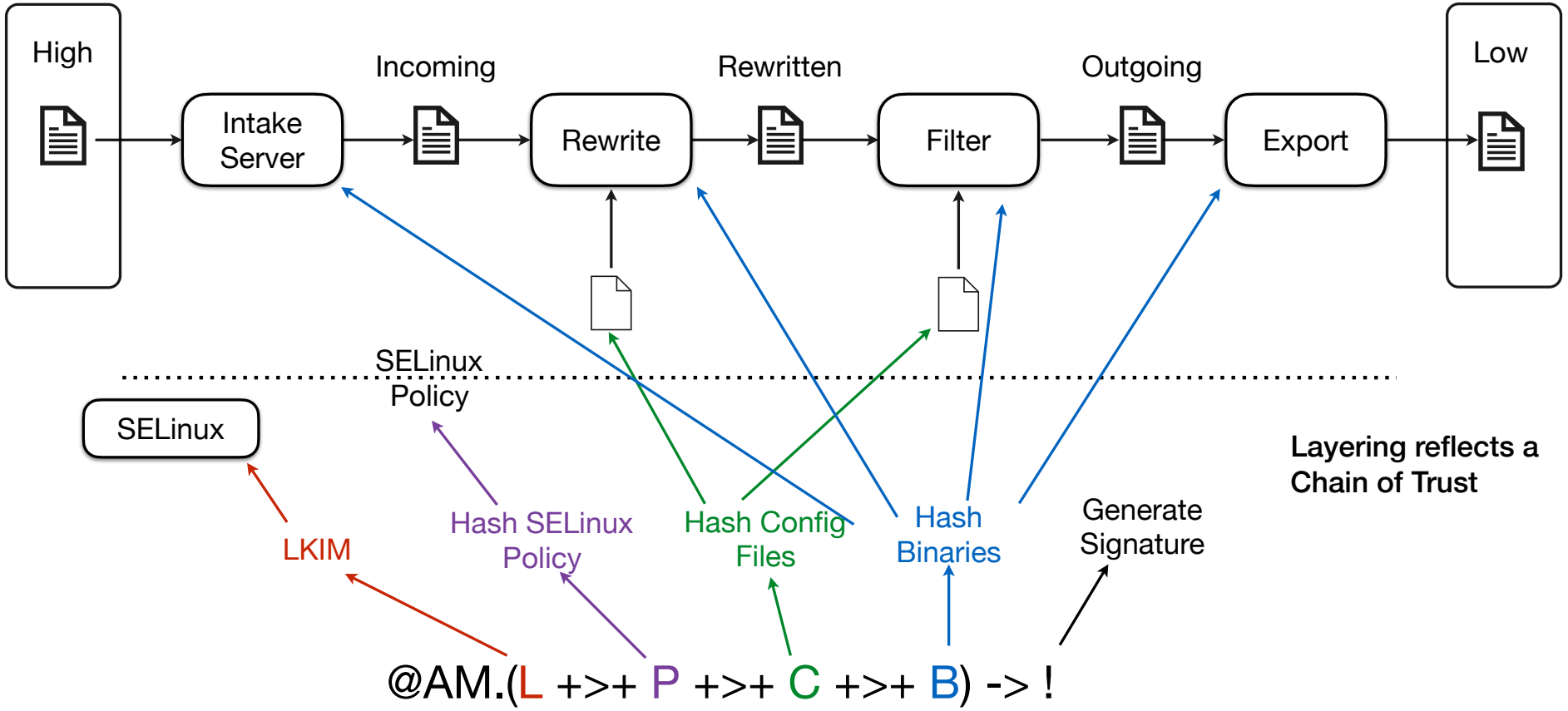
- Long running attestations
  - to our knowledge no one has studied long-running experiments on complex attestations
  - evaluating various flexible mechanisms
- Modeling attacks
  - sneaking by the attestation/appraisal system
  - directly attacking the attestation/appraisal system
- Attestation Test Bed
  - controlled evaluation environment
  - mixed architecture - ARM, Intel, IoT, Xen, KVM

Cross Domain System



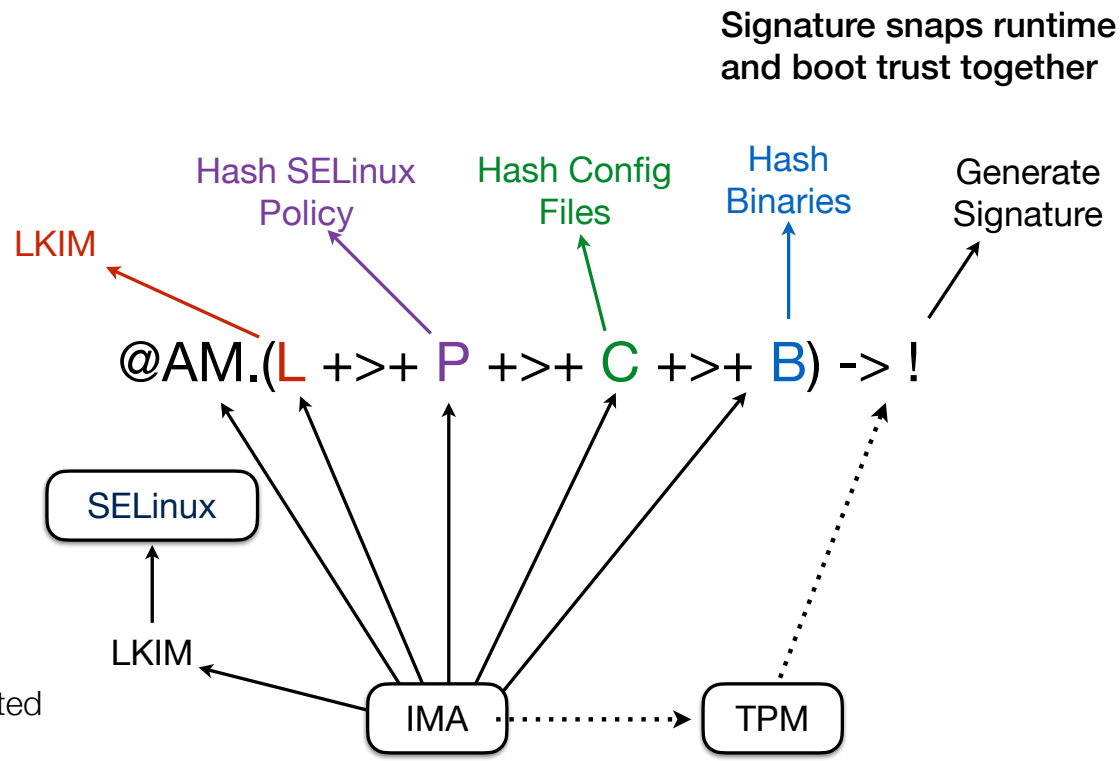
- Moving messages between security domains
  - intake receives a message from the high-side writes to incoming buffer
  - rewriter reads from the incoming buffer, applies rewrite rules, and writes to rewritten buffer
  - filter reads from the rewritten buffer, applies address filtering rules, and writes to outgoing buffer
  - export reads from outgoing buffer and outputs to low-side client
- Configuration
  - rewrite and filter processes have configuration files
  - SELinux policy enforces flow through the system
- Messages reaching the low-side client must be:
  - received from the high-side client
  - rewritten by a properly configured rewriter
  - filtered by a properly configured filter

ASPs and Protocol



Protecting Attestation at Runtime

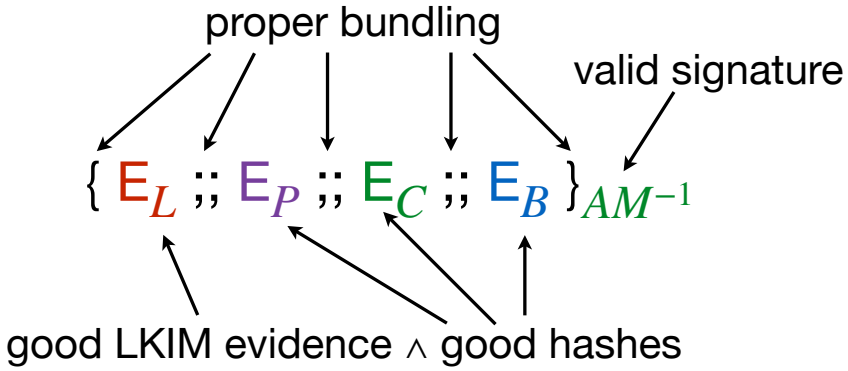
- Runtime IMA Measurements
  - Policy specifies hashes for ASPs
  - Policy specifies a hash for AM
  - IMA writes log to TPM PCR 10 (currently unused)
- AM^{-1} Signature
  - key is TPM resident
  - SELinux controls access to key blob
  - IMA EVM controls key blob permissions
- Linux
  - measured during boot using Invary LKIM
  - remeasured at runtime using Invary LKIM
  - SELinux policy dumped and hashed
  - good signature memorializes boot
  - the AM's key is not available if boot policy is violated



Appraising Attestation Results

- Trustworthy target if
  - proper bundling
  - evidence satisfies appraisal policy
  - valid signature
- Proper bundling
  - indicates measurement ordering
  - generated by verified AM
- Satisfies appraisal policy
  - E_L - LKIM policy appraisal
  - E_{P-B} - Hashes checked against golden values
  - AM^{-1} - Signature checked with public AM key
- Provisioning requirements
  - gather good hashes
  - generate and distribute AM key pair
  - define LKIM appraisal policy

@AM.(L +>+ P +>+ C +>+ B) -> !



proper bundling
∧ satisfies appraisal policy
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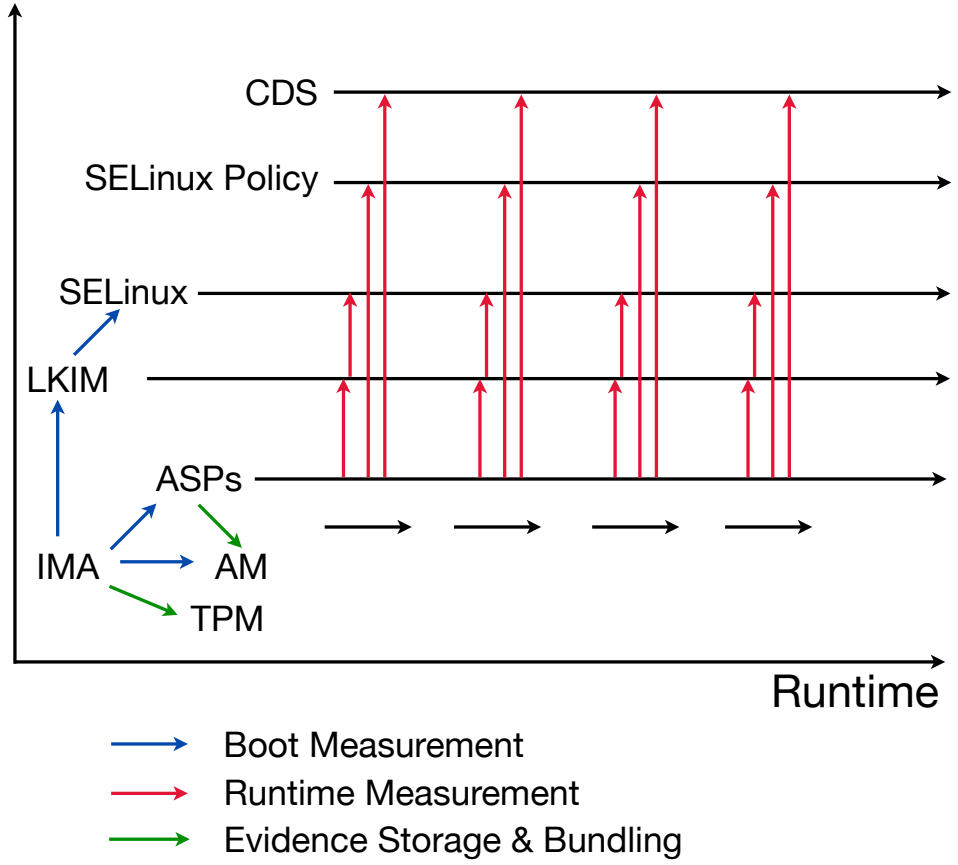
Layered Runtime Attestation

- Boot to an initial measured state
  - establish running AM with bound key
  - IMA hashes and checks AM on invocation
  - AM^{-1} is available on good PCRs, good AM and encrypted blob
- Remeasure at runtime
  - AM executes Copland attestation protocols
  - ASPs gather information after IMA check by IMA
  - Protocol execution bundles evidence
  - AM signs gathered evidence with AM^{-1}
- Appraisal and Remeasurement
  - AM communicates with relying party
  - Appraisal may occur in AM, Relying Party, or third party appraiser
  - Remeasurement may occur in AM or Relying party
- PCRs and AM^{-1} are the trust link
  - boot measured into PCRs
  - signing key sealed by PCRs and protected by SELinux and IMA
  - signature carries trust meta-evidence
- Layering builds trust bottom up
  - dependencies measured first
  - bundled evidence reflects measurement order
  - verified in earlier work



Adversary Goals and Attack Mechanisms

The adversary's primary goal is convincing a relying party to trust something it should not

The adversary's secondary goal is convincing a relying party not to trust something it should

- Attacks on attestation target
  - change target without impacting policy compliance
  - change target and repair before measurement (TOCTAU)
- Attacks on evidence and meta-evidence
  - post measurement changes directly to evidence
  - generate signatures using incorrect components
  - cache alterations and poisoning
  - evidence package replay and spoofing
- Attacks on attestation infrastructure
  - compromise AM identity and steal AM's signing key
  - compromise AM execution and ASP ordering
  - alter ASPs to report incorrect, but compliant evidence
  - attack crypto and attestation protocol infrastructure
  - incorrectly report appraisal results
- Attacks on system infrastructure
  - compromises to hardware
  - changing boot images and boot order
  - TPM, IMA, and SELinux policy modifications

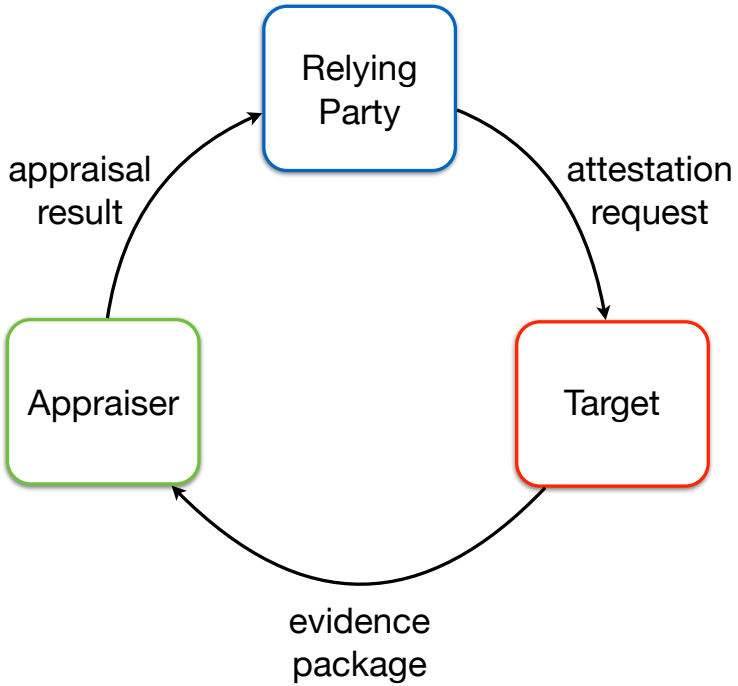
Testing Attestation and Appraisal

- Components targeted in testing
  - boot measurement infrastructure
  - runtime measurement infrastructure
  - CDS system configuration and components
- Attacks on configurations
  - altering component configuration
  - changing SELinux, IMA and TPM policy
- Attacks on executables
  - changing component runtime behavior
  - replacing or modifying executables
- Attacks across lifecycle
  - boot time attacks
  - runtime attacks
  - transitioning from boot trust to runtime trust

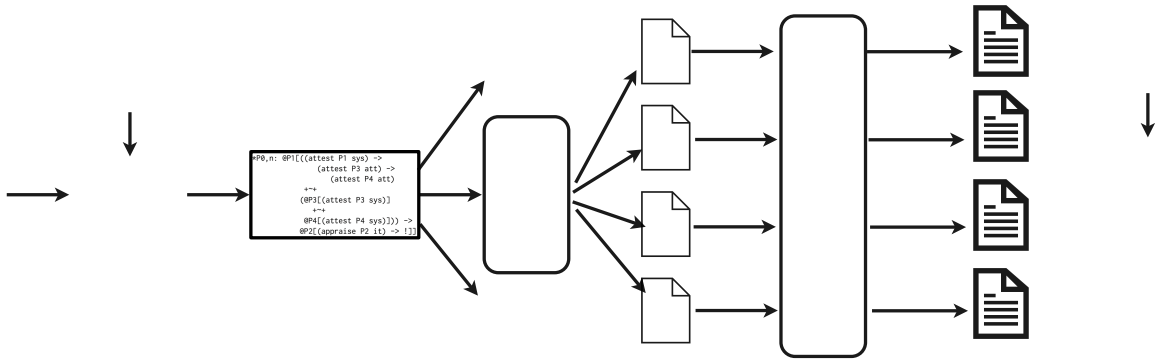
Attacks Considered		
Component	Configuration	Executable
Hardware	✘	✘
TPM	✔	✘
Bootloader	✔	✘
LKIM	✔	✘
Kernel	✔	✔
IMA	✔	✔
SELinux	✔	✔
AMs	✔	✔
ASPs	✔	✔
CDS Comp	✔	✔

What We Learned

- Boot transition to runtime is messy
  - boot trust must be reflected in runtime appraisal
  - yet there is no moment when runtime starts
  - integration with low level apparatus helps (IMA, SELinux, TPM)
- The AM's signing key is critical
  - a good AM key signature memorializes trusted boot
  - AM key compromise invalidates all attestation results
  - the AM key is long-lived and difficult to protect
- Design for attestation
  - short lived processes are more difficult to attack
  - processes run only when needed
  - dependencies first and layering is essential
  - separate infrastructure from application
- Mind the Gap (TOCTOU)
  - Time between measurement and use
  - IMA hash -> IMA startup
  - Binary runtime hash and use
- Assumptions and Interactions
  - boot to a bad state without SELinux
  - grab the AM^{-1} key blob that TPM will not unseal
  - reboot to a good state with good PCR values
  - use the AM^{-1} key blob from the bad boot



Next Up…



- Long-running attestation
  - re-measurement intervals
  - evidence caching and behavior
  - evidence behavior over time
- Larger layered targets
  - multi-machine attestations and appraisal
  - evidence bundling and abstraction
  - external appraisal services
- Evidence as program understanding
  - formal notions of measurement and abstraction
  - temporal evidence properties
  - composition evidence properties
- Protocols From Systems
  - move the user from protocol authoring to system modeling
  - generate protocols from system models
  - include adversary models
- Put Evidence Semantics to Work
  - linter to provide protocol writing guidance
  - type analysis to predict protocol behavior
  - understanding protocol orderings
- Separation issues in AM and ASPs
  - compartmentalization of ASP execution
  - separation within the AM
  - verus modeling for ASPs

Odds and Ends

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- KU/FBI CyberSecurity Conference, April 2025
- Research agreement between KU and Invary, LLC for commercialization
- Evaluation at KCNSC for potential deployment
- Meeting bi-weekly with MITRE and NSA Liaisons
- Presentations at CCS'25, HCSS'25, LSS'25
- Petz, A., W. Thomas, A. Fritz, T. Barclay, L. Schmalz, and Perry Alexander, "Verified Configuration and Deployment of Layered Attestation Managers," *Proceedings of the 22nd International Conference on Software Engineering and Formal Methods (SEFM'24)*, LNCS 15280, November 4-8, 2024, Aveiro, Portugal.
- Johnson, S. and P. Alexander, "Ordering Attestation Protocols," n preparation for *Network and Distributed System Security (NDSS'26) Symposium*, San Diego, California, February 23-27, 2026.
- Thomas, W., L. Schmalz, A. Petz, P. Alexander, J. Guttman, J. Carter, "Layered Attestation in Action: Attesting to a Cross-Domain Solution," in preparation for *Network and Distributed System Security (NDSS'26) Symposium*, San Diego, California, February 23-27, 2026.