Trust

What it is and how to get it

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What is Trust?

"An entity can be trusted if it always behaves in the expected manner for the intended purpose"[1]

[1] *The Ten Page Introduction to Trusted Computing* by Andrew Martin

Properties of Trust

- Unambiguous identification
- Unimpeded operation
- First-hand observation of good behavior *or* indirect experience of good behavior by a trusted third party

Required Capabilities for Establishing Trust

- *Strong Identification* — An unambiguous, immutable identifier associated with the platform.
- *Reporting Configuration* — An unambiguous identification mechanism for software and hardware running on the platform.
- *Reporting Behavior* — A mechanism for observing and reporting execution behavior.

Tools for Trust

- $\#X$ — Hash of X
  - $\#X$ is unique for each X
  - Guessing X from $\#X$ is impossible
- $\{X\}_Y$ — Encrypt X with Y
  - X cannot be obtained from $\{X\}_Y$ without Y
  - Guessing X from $\{X\}_Y$ is impossible
  - Guessing Y is impossible
- $[X]_{Y^{-1}}$ — Sign X with Y^{-1}
  - $[X]_{Y^{-1}}$ is unique for every X and Y^{-1} pair
  - Guessing $[X]_{Y^{-1}}$ from X is impossible
- $M \mid \#X$ — Extend M with $\#X$
  - Concatenate M with $\#X$ and hash the result
  - Ideal $M \mid \#X$ unique for M and X

Tools for Trust

- $(X, \{X^{-1}\}_{Y^{-1}})$ — Wrap X with Y^{-1}
  - Can use X for encryption and signature checking
  - Cannot use X^{-1} for decryption or signing without Y^{-1}
- $(D, \{C\})$ — Seal D to configuration C
  - D is not available if system is not in configuration C
  - Usually accompanied by encryption
- $(\{SK\}_K, \{D\}_{SK})$ — Envelope D with K
  - Encrypt large data D with session key SK
  - Encrypt SK with K
  - D behaves as if encrypted with K
- $[[(A, B)]]_{Y^{-1}}$ — Certify binding of A and B with Y^{-1}
  - Y signs (A, B) with private key Y^{-1}
  - Certificate is checked using Y
  - Valid signature provides evidence A and B are bound together

Wrapping and Chaining Keys

Wrapping A Key

$wrap(X, Y) = (X, \{X^{-1}\}_{Y^{-1}})$

- X^{-1} is encrypted with Y^{-1} while X is clear
- $\{D\}_X$ and checking $[D]_{X^{-1}}$ may be done without Y
- Decrypting $\{D\}_X$ and generating $[D]_{X^{-1}}$ require Y

Chaining Keys

$(X_0, \{X_0^{-1}\}_{X_1^{-1}}), (X_1, \{X_1^{-1}\}_{X_2^{-1}}) \dots (X_{n-1}, \{X_{n-1}^{-1}\}_{X_n^{-1}})$

- Each key depends on the previous key
- If the root key is trustworthy the chain is trustworthy

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Wrapped Keys

A wrapped key must be installed before use and depends on installation of its wrapping key

- Installing $(K, \{K^{-1}\}_{J^{-1}})$ provides a handle for use with other commands
  - The key handle is a pointer into the TPM
  - Cannot be used to access the key outside the TPM
- $(K, \{K^{-1}\}_{J^{-1}})$ installs if J is installed and usable
  - Key may be installed by not usable if PCRs are not configured or authentication fails
  - $(K, \{K^{-1}\}_{SRK^{-1}})$ wraps a key with a TPM's storage root key

Sealing Data

Sealing to State

$(D, \{C\})$ — Seal D to configuration C

- D is protected by a key or other mechanism
- C describes an acceptable system state
- D cannot be accessed if system is not in state C
- Used to protect data even when system is mis-configured

Enveloping

$$envelope(K, D) = (\{SK\}_K, \{D\}_{SK})$$

- *SK* is a symmetric session key for bulk encryption
- *D* is encrypted with *SK*
- *SK* is encrypted with *K*
- *D* is protected as if encrypted with *K*

Certificates and Certification

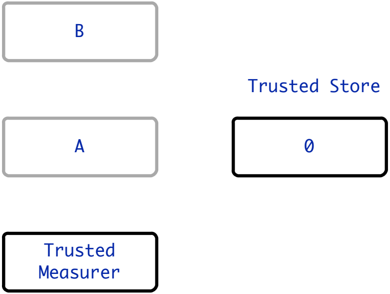
$$[[(A, B)]]_{Y^{-1}} = [(A, B)]_{Y^{-1}}$$

- (A, B) associates A with B
- Y certifies the association by signing with Y^{-1}
- Certificate is checked using Y
- If we trust Y, then we trust the binding of A to B

Chaining Measurement — Gathering Evidence

We would like to start *A* and *B* while gathering evidence for determining trust

- Start with a root measurer and store that are trusted *a priori*



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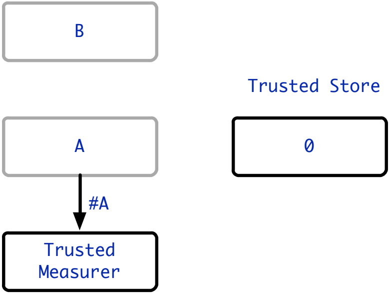

Chaining Measurement — Gathering Evidence

We would like to start *A* and *B* while gathering evidence for determining trust

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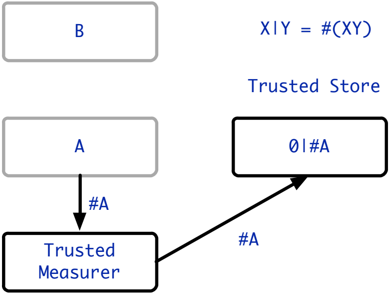
- Store the measurement of the new software



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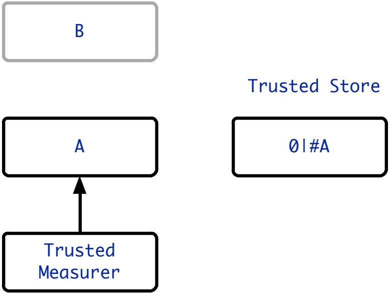

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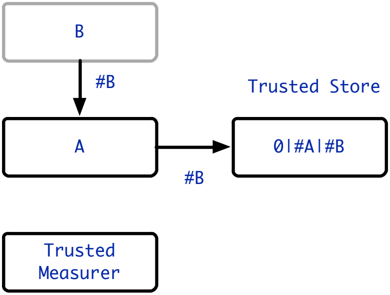
- Launch the new software
- Repeat for each system software component



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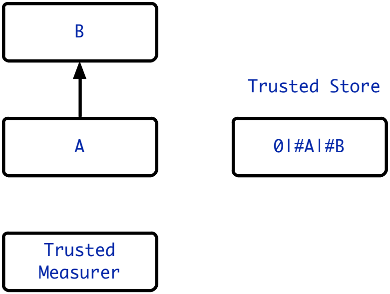

Appraisal — What Do We Know?

Measurement $\neq$ trust — Measurements must be appraised

- Determine if $0 \mid \#A \mid \#B$ is correct
  - Calculate a *golden hash* from A and B
  - Compare golden hash with $0 \mid \#A \mid \#B$ from trusted store
  - Correct $0 \mid \#A \mid \#B$ implies trusted boot
- Correct $0 \mid \#A \mid \#B$ implies A and B must be correct
  - Correct $0 \mid \#A \mid \#B$ implies $\#A$ and $\#B$ are the correct hashes
  - Correct $\#A$ and $\#B$ implies A and B are the correct binaries
  - A includes hash and launch functions
- Correct $0 \mid \#A \mid \#B$ implies measurement occurred in the right order
  - $\#(XY) \neq \#(YX)$
  - Trusted store started with 0

Appraisal — But Why Trust B?

A chain exists from the Trusted Measurer and Trusted Store to B

- Trusted Measurer and Trusted Store are trusted *a priori*
- A is trusted to be A because its measurement is:
  - Correct
  - Taken by a trusted party (Trusted Measurer)
  - Stored by a trusted party (Trusted Store)
- B is trusted to be B because its measurement is:
  - Correct
  - Taken by a trusted party (A)
  - Stored by a trusted party (Trusted Store)
  - If A's ability to measure B were compromised, $\#A$ would be wrong
- and so on and so on...

Trust is a Preorder

$T^{\mathsf{x}}[\mathsf{y}]$ is an homogeneous relation over actors that is true when *x trusts y*. $T^{\mathsf{x}}[\mathsf{y}]$ is by definition a Preorder:

- Reflexive — $\forall x \cdot T^{\mathsf{x}}[\mathsf{x}]$
- Transitive — $\forall x, y, z \cdot T^{\mathsf{x}}[\mathsf{y}] \wedge T^{\mathsf{y}}[\mathsf{z}] \Rightarrow T^{\mathsf{x}}[\mathsf{z}]$

Measured Boot gathers evidence to check trust relationships.

Trust is a Preorder

A *chain of trust* from X_0 to X_n:

$$T^{\mathsf{X}_0}[\mathsf{X}_1] \wedge T^{\mathsf{X}_1}[\mathsf{X}_2] \wedge \ldots \wedge T^{\mathsf{X}_{n-1}}[\mathsf{X}_n]$$

- If X_0 is trusted, then X_n is trusted
- X_0 is called a *root-of-trust*
- Establishing trust chains defines a framework for measurement
- Measurement provides evidence that trust chains are not violated
- Appraisal checks evidence to assess trust chains

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Trusted Platform Module

The *Trusted Platform Module (TPM)* is a cryptography co-processor for trust.

- Endorsement Key (EK) — factory generated asymmetric key that uniquely identifies the TPM
- Attestation Instance Key (AIK) — `TPM_CreateIdentity` generated asymmetric key alias for the EK
- Storage Root Key (SRK) — `TPM_TakeOwnership` generated asymmetric key that encrypts data associated with the TPM
- Platform Configuration Registers (PCRs) — protected registers for storing and extending hashes
- NVRAM — Non-volatile storage associated with the TPM

Endorsement Key

- Asymmetric key generated at TPM fabrication
- EK^{-1} is protected by the TPM
- *EK* by convention is managed by a Certificate Authority
  - Binds *EK* with a platform
  - Classic trusted third party
- Only used for encryption
- Attestation Instance Keys (AIK) are aliases for the EK
  - Used for signing
  - Authorized by the EK

Storage Root Key

- Asymmetric key generated by `TPM_TakeOwnership`
- SRK^{-1} is protected by the TPM
- *SRK* is available for encryption
- Used as the root for chaining keys by *wrapping*
  - A wrapped key is an asymmetric key pair with it's private key sealed
  - Safe to share the entire key
  - Only usable in the presence of the wrapping key with expected PCRs

Platform Configuration Registers

- Operations on PCRs
  - Extension — Hash a new value juxtaposed with the existing PCR value
  - Reset — Set to 0
  - Set — Set to a known value
- Operations using PCRs
  - Sealing data — PCR state dependent encryption
  - Wrapping keys — PCR state dependent encryption of a private key
  - Quote — Reporting PCR values to a third party
- Properties
  - Locality — Access control like OS security rings
  - Resettable — PCR can be reset to known value after *SENTER*
  - Many others that we don't need yet

Resetting PCRs

Non-Resettable

- History since reboot
- Reset only on reboot
- Good for recording trajectory

Resettable

- No history
- Reset before use
- Good for one-off user data

- Reset requires appropriate permissions based on locality
- A PCR is resettable if defined in platform spec

Locality = Access Control for PCRs

- Each PCR is assigned a locality
- Only processes with locality greater than or equal a PCR's locality may modify it
- Increases monotonically starting at `SENTER` invocation

Locality and What Runs There

Locality	*Purpose*
4	Trusted Hardware/SINIT Policy
3	Other MLE Components
2	Operating System
1	Applications Static
0	RTM/Legacy

Locality Rules of Thumb

- Only SENTER runs in locality 4
- Only SINIT runs in locality 3
- OS and core system run in locality 2
- Applications run in locality 1
- Locality 0 is rarely used

Roots of Trust

A *root of trust* provides a basis for transitively building trust. Roots of trust are trusted implicitly.

There are three important Roots of Trust:

- Root of Trust for Measurement (RTM)
- Root of Trust for Reporting (RTR)
- Root of Trust for Storage (RTS)

Root of Trust for Measurement

A *Root of Trust for Measurement* is trusted to take the base system measurement.

- A hash function called on an initial code base from a protected execution environment
- Starts the measurement process during boot
- In the Intel TXT process the RTM is `SENTER` implemented on the processor

Root of Trust for Reporting

A *Root of Trust for Reporting* is trusted to guarantee the integrity of the base system report or quote

- A protected key used for authenticating reports
- In the Intel TXT processes this is the TPM's Endorsement Key (EK)
- Created and bound to its platform by the TPM foundry
- EK^{-1} is stored in the TPM and cannot be accessed by any entity other than the TPM
- EK is available for encrypting data for the TPM
- EK^{-1} is used for decrypting data inside the TPM
- Linking EK to its platform is done by a trusted Certificate Authority (CA)

Root of Trust for Storage

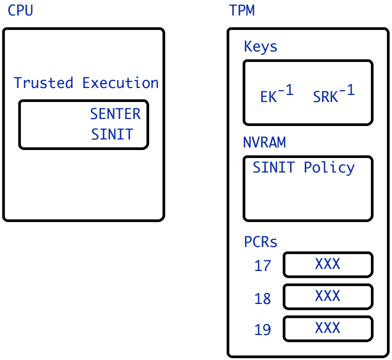
A *Root of Trust for Storage* is trusted to protect stored data

- A key stored in a protected location
- In the Intel TXT boot process this is the TPM's Storage Root Key (SRK)
- Created by `TPM_TakeOwnership`
- SRK^{-1} is stored in the TPM and cannot be accessed by any entity other than the TPM
- *SRK* is available for encrypting data for the TPM
- SRK is used for protecting other keys

One Step from Roots of Trust

Roots of trust are used to build a trusted system from boot.

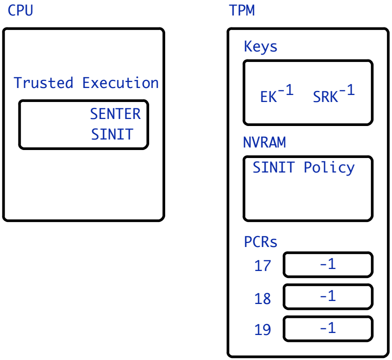
- Power-on reset



One Step from Roots of Trust

Roots of trust are used to build a trusted system from boot.

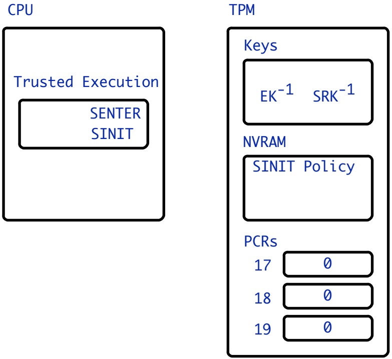
- Power-on reset
- Resettable PCRs set to -1



One Step from Roots of Trust

Roots of trust are used to build a trusted system from boot.

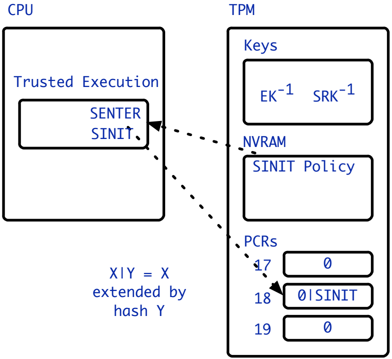
- Power-on reset
- Resettable PCRs set to -1
- `SENTER` called, resets resettable PCRs to 0



One Step from Roots of Trust

Roots of trust are used to build a trusted system from boot.

- Power-on reset
- Resettable PCRs set to -1
- `SENTER` called, resets resettable PCRs to 0
- `SENTER` measures `SINIT` policy into PCR 18



What We Know From Good PCR 18

A good value in PCR 18 tells us:

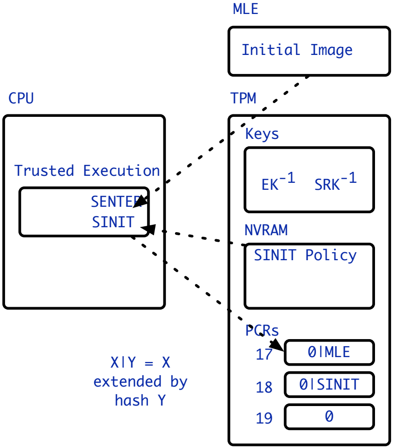
- `SENTER` was called — Resetting PCR 18 starts measurements at 0 rather than -1
- `SINIT` was measured by `SENTER` — Only `SENTER` can extend PCR 18
- `SINIT` uses the correct policy — PCR 18 is extended with `SINIT` measurement policy
- `SENTER` ran before `SINIT` was measured — $A \mid B \neq B \mid A$

Measurement $\neq$ Trust

Measurements must be appraised to determine trust.

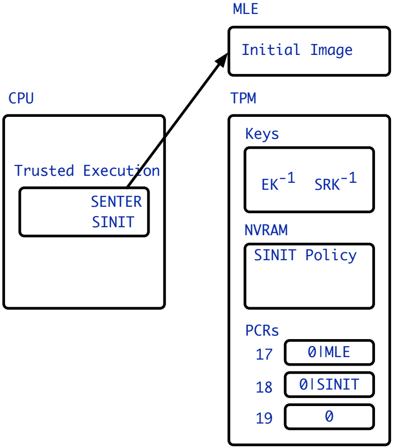
Two Steps from Roots of Trust

- SINIT measures the Measured Launch Environment (MLE) using measured SINIT policy
- SINIT returns control to SENTER



Two Steps from Roots of Trust

- SINIT measures the Measured Launch Environment (MLE) using measured SINIT policy
- SINIT returns control to SENTER
- SENTER invokes the MLE



What We Know From Good PCRs

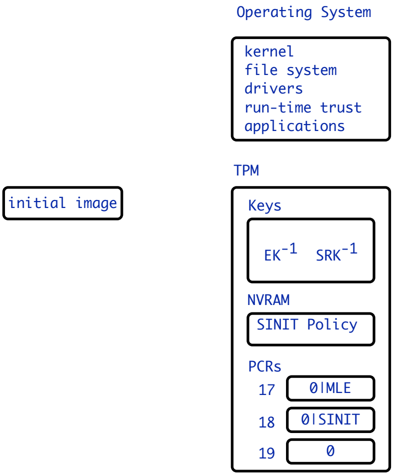
- `SENTER` was called — Resetting PCR 18 starts measurement sequence at 0 rather than -1
- `SINIT` policy was measured by `SENTER` — Only `SENTER` can extend PCR 18
- `SINIT` uses the correct policy — PCR 18 is extended with `SINIT` measurement policy
- `SENTER` ran before `SINIT` — $0 \mid \#SINIT \neq -1 \mid \#SINIT$
- `MLE` is good — Measured by good `SINIT` into PCR

Boot is generic until the `MLE` starts

MLE is the beginnings of the operating system.

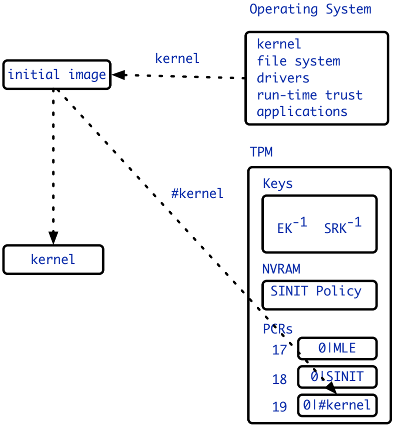
Boot the MLE

- SENTER starts the MLE
  - SENTER starts the initial image
  - Initial image starts the system



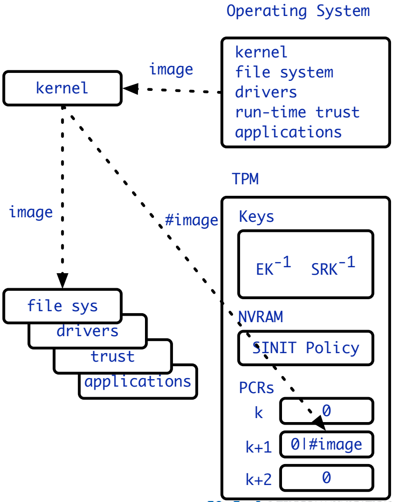
Boot the MLE

- `SENTER` starts the MLE
  - `SENTER` starts the initial image
  - Initial image starts the system
- Initial image initialized the kernel
  - Measures the kernel into the TPM
  - Starts the kernel



Boot the MLE

- `SENTER` starts the MLE
  - `SENTER` starts the initial image
  - Initial image starts the system
- Initial image initialized the kernel
  - Measures the kernel into the TPM
  - Starts the kernel
- Kernel boots the system
  - Measures remaining images into the TPM
  - Starts remaining images
  - Measures application into the TPM
  - Starts the application



Boot the MLE

- SENTER starts the MLE
  - SENTER starts the initial image
  - Initial image starts the system
- Initial image initialized the kernel
  - Measures the kernel into the TPM
  - Starts the kernel
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  - Starts remaining images
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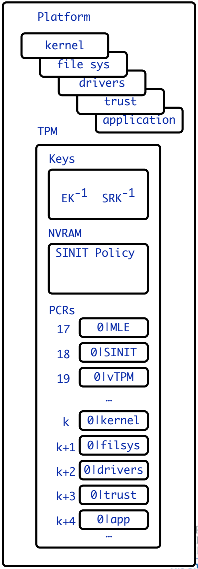


What we know from good PCRs

Built from Good Parts

We can construct a proof that the platform is constructed correctly from PCR contents

- SINIT measured the right initial image - PCR 18 measurement and we trust `SENTER`
- The right initial image started - PCR 17 measurement and we trust `SENTER`, `SINIT` and `SINIT` Policy is measured
- The right kernel started - PCR 19 measurement and we trust `SENTER`, `SINIT`, and initial image is measured
- The right system components started - PCRs and the kernel is measured
- The right application started - TPM PCRs and the kernel is measured

Chaining Trust (Reprise)

- Trust is transitive
  - $T^x[y] \wedge T^y[z] \Rightarrow T^x[z]$
  - Construct evidence trust chains
  - Remember “directly observed or indirectly observed by a trusted third party”
- Roots of Trust define the “root” for trust
  - Use Roots of Trust to establish base for chain
  - SENTER/SINIT is the Trusted Measurer
  - SRK and TPM is the Trusted Storage Root (Unused so far)
  - EK and TPM is the Trusted Reporter (Coming next)
- Extend chains of trust by measuring before executing

Getting a Quote

A *quote* is a signed data package generated by a TPM used to establish trust

- $q = [\langle n, pcr \rangle]_{AIK^{-1}}$
  - n - A nonce or other data
  - pcr - A PCR composite generated from TPM PCRs
  - AIK^{-1} - An alias for EK^{-1} used for signing instead of EK^{-1}
- Generated by the TPM with command `TPM_Quote`

Attestation Identity Key

An *AIK* is A wrapped TPM key bound to an EK^{-1} usable only in the TPM that generated it in the right state

- $\{(AIK^{-1}, \{pcr\})\}_{EK^{-1}}$ - the AIK^{-1} encrypted with EK^{-1} and sealed to *pcr* values.
- $\{(AIK^{-1}, \{pcr\})\}_{EK^{-1}}$ decrypts and installs only when
  - *pcr* matches the TPM's PCRs at decryption time
  - EK^{-1} is the TPM's endorsement key
- Protected by a combination of encryption and state
- Generated by a TPM

Appraising a Quote

Given q of the form:

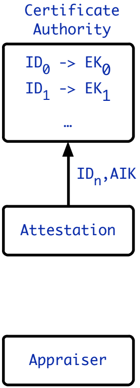
$$q = [\langle n, pcr \rangle]_{AIK^{-1}}$$

1. Signature check using *AIK* verifies authenticity
   - Signature was generated by a TPM with AIK installed
   - Appraiser must know *AIK*
2. *pcr* check verifies built from good parts in the right order
   - Compare PCR composite to known good PCR composite
   - Composite generated from desired golden PCR values
3. Nonce check guarantees freshness
   - Nonce is random and known to the appraiser
   - Sent to the target during appraisal

Certifying AIK

Assume a trusted Certificate Authority (CA) that maintains links from ID to *EK* with well-known public key *CA*

- ID_n requests *AIK* certification from CA



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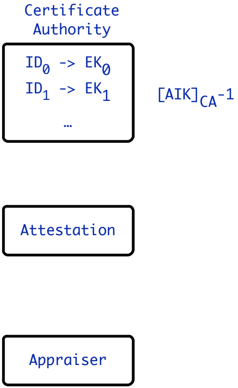

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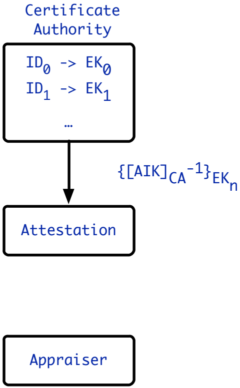
- CA encrypts $[AIK]_{CA^{-1}}$ with ID_n's EK_n



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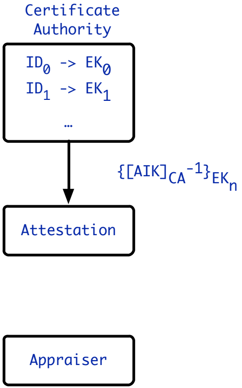
- CA encrypts $[AIK]_{CA^{-1}}$ with ID_n's EK_n
- CA sends $\{[AIK]_{CA^{-1}}\}_{EK_n}$ to ID_n



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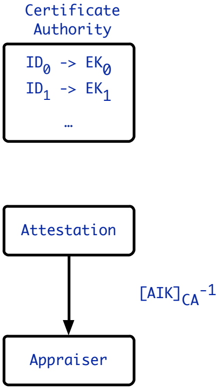
- CA encrypts $[AIK]_{CA^{-1}}$ with ID_n's EK_n
- CA sends $\{[AIK]_{CA^{-1}}\}_{EK_n}$ to ID_n
- ID_n decrypts encrypted AIK with EK_n^{-1}



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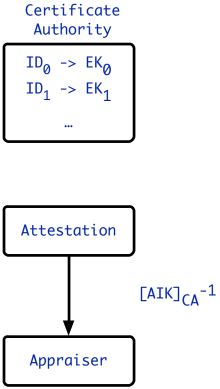
- CA encrypts $[AIK]_{CA^{-1}}$ with ID_n's EK_n
- CA sends $\{[AIK]_{CA^{-1}}\}_{EK_n}$ to ID_n
- ID_n decrypts encrypted AIK with EK_n^{-1}
- ID_n sends $[AIK]_{CA^{-1}}$ to appraiser



Why Believe AIK Belongs to ID_n?

Cryptographic evidence ensures AIK is an alias for the right EK

- Only the CA can generate $[AIK]_{CA^{-1}}$
- CA is trusted to know $ID_n \rightarrow EK_n$
- CA is trusted to generate $\{[AIK]_{CA^{-1}}\}_{EK_n}$
- Only ID_n can decrypt $\{[AIK]_{CA^{-1}}\}_{EK_n}$
- Appraiser can check $[AIK]_{CA^{-1}}$ to ensure use of trusted CA
- If Appraiser can use AIK then it was decrypted by ID_n

AIK is now a certified alias for EK used for signing

Using Protocol Notation

Protocol notation specifies communication:

$$Sender \rightarrow Receiver : Message$$

Key Certification Protocol

$$\begin{aligned}
ID_n &\rightarrow CA : AIK \\
CA &\rightarrow ID_n : \{[AIK]_{CA^{-1}}\}_{EK_n} \\
ID_n &\rightarrow App : [AIK]_{CA^{-1}}, [\langle n, pcr \rangle]_{AIK^{-1}}
\end{aligned} \quad (1)$$

Remote Data Acquisition

Boot and appraise remote system for covert data acquisition

- Target reset triggers target boot initialization
- Target initial boot goes through BIOS and device startup
- Target secondary boot establishes comm link and “phones home”
- Appraiser evaluates target
- Appraiser responds to target with OS image
- Target boots OS image
- Target begins operation
- Appraiser evaluates target
- Target begins data acquisition and transmission

Assumptions

General assumptions:

- Nonces, keys and hashes cannot be guessed
- Perfect cryptography
- All messages are carried by the adversary

System specific assumptions:

- Secure communication subsystem is trustworthy
- Target knows what to communicate with
- TPM present on the target
- AIK is established and certified prior to system launch

Designing A Trusted System

What assets should be protected and how?

- What assets must be handled confidentially?
- What assets must be handled with integrity?
- What assets and behaviors must be appraised?
- What behaviors must be prevented?

Some initial observations:

- Initial boot software - integrity, must be appraised
- Communication addresses - confidentiality
- Hardware and tamper protections - integrity, must be appraised
- Operating system - integrity, must be appraised
- Data transmission key - confidentiality

Trust

Trust is:

- Strong identification
- Direct observation of good behavior
- Indirect observation of good behavior by a trusted third party

Late Launch is:

- Initial measurement taken and stored by roots of trust for measurement and storage
- Reporting performed by root of trust for reporting
- Trust chains transitively from roots of trust outward
- System is constructed of good parts

Roots of Trust

- Root of trust for measurement
  - SENTER for launch
  - Initial measurement taken by SINIT
  - Hardware-based TPM initialization
- Root of trust for storage
  - TPM storage root key (SRK)
  - Locality enforcement
  - TPM separation
- Root of trust for reporting
  - TPM endorsement key (EK)
  - TPM separation

Initial Design Decisions

Design Decisions

- What are measurement responsibilities?
- What is in the MLE?
- Where are measurements stored?
- How is locality assigned?

Measurement Responsibilities

- `SENTER` measures `SINIT` policy
- `SINIT` measures the Measured Launch Environment (MLE)
- Initial boot measures hardware and Secondary boot software
- Secondary boot measures OS
- OS measures components as they start

Measurement Relation

$$\texttt{SENTER} \rightarrow \texttt{SINIT} \rightarrow \texttt{MLE} \rightarrow \texttt{OS} \rightarrow \texttt{app}$$

- No measurement loops
- Everything is measured

Traditional Measurement Storage

PCR	*Contents*
0–15	Static RTM
16	Debug
17	Locality 4 measurements by `SENTER`
18	Locality 3 measurements by `SINIT`
19	Locality 2 measurements by MLE and OS
20	Locality 1 measurements by applications
21–22	T/OS controlled
23	Application specific measurements

Need a PCR?

- Available non-resettable PCRs are 8-15
- Available resettable PCRs are 16,23

What is in the MLE?

- Anything measured by SINIT is in the MLE by definition
- MLE could be the initial boot image or the entire boot image
- How much granularity desired in measurements?

What is in the MLE?

- Initial boot image
- Nothing more

Where Are Measurements Stored?

- Initial measurement storage location is standard
- Typically 1 hash per measurement, but could be a sequence

PCRs 17 and 18

- SINIT Policy measured by `SENTER` into PCR 17
- MLE Measured by `SINIT` into PCR 18
- PCRs 17 & 18 are non-resettable

Where Are Measurements Stored?

- Later measurements must be designed
- One big hash, many hashes, one PCR, many PCRs

PCRs 19 and 20

- OS measured into PCR 19
- Application(s) measured into PCR 20

What are the Measurements?

- Measure the OS
  - OS measured as one hash
  - OS measured as a hash sequence by the OS startup
- Applications measured as one hash each
- Ordering application measurement?
  - Enforce application hash order by sequencing startup
  - Use multiple PCRs
  - Produce multiple good hashes in appraiser
- Measurement *must* be performed as components are started

Measurement Options and Appraisal

- Measurement granularity
  - One hash says good or bad for all system binaries and is simple to take
  - Many hashes extending a PCR says good or bad for all system binaries including order
- One or Many PCRs
  - One PCR says good or bad for all system binaries with order
  - Many PCRs says good or bad for individual system binaries without order
- Resettable or Non-Resettable
  - Resettable ignores history prior to reset
  - Non-resettable captures history from system startup

Where are Measurements Stored? (Redux)

- Poky Linux is measured as one hash into PCR 19
  - Need to know good or bad on startup
  - Using Poky Linux unmodified
- Application is measured as one hash into PCR 20
  - Need to know good or bad on startup
  - Only one application

PCRs 19 and 20

- OS measured into PCR 19 by secondary boot prior to start
- Application(s) measured into PCR 20 by OS prior to start

How is Locality Assigned?

- No reason to deviate from standard locality mapping
- No reason to reset PCRs

Locality Assignment

- PCR 17 - Locality 4, non-resettable
- PCR 18 - Locality 3, non-resettable
- PCR 19 - Locality 2, non-resettable
- PCR 20 - Locality 1, non-resettable

Appraisal

An appraiser evaluates a target by requesting and examining a *quote*

- The appraiser requests a quote from the target specifying:
  - PCRs to be included
  - A fresh nonce
- The target returns a quote containing:
  - PCR composite as evidence of target state
  - The original nonce as evidence of freshness
  - AIK^{-1} signature as evidence of integrity and authenticity

Generating a Quote

Quote Structure

$$q = [n, PCR]_{AIK^{-1}}$$

- Generate and certify an *AIK*
  - TPM generates an *AIK* wrapped by EK^{-1}
  - Privacy CA generates a certificate encrypted with *EK*
  - Only generating TPM can decrypt the certificate
- Install the *AIK*
  - AIK is wrapped thus AIK^{-1} and inaccessible outside the generating TPM
  - Installing AIK makes it available to the TPM
- Request a quote from the TPM
  - Nonce, PCRs needed, and AIK handle
  - Only the TPM that generated the AIK can generate the quote signature

Evaluating a Quote

- Appraiser must have:
  - Public *CA* key
  - Public *AIK* key
  - Original nonce
  - Expected PCR values
- Checking the quote
  - Check the *AIK* certificate signature using public *CA*
  - Check the quote signature using public *AIK*
  - Check the quote nonce value using original nonce value
  - Check the PCR composite against an expected golden value

What the Appraiser Knows

- *AIK* belongs to the target's TPM from CA certificate check
- The quote was generated using *AIK* installed in the target's TPM from quote signature check
- The quote was generated in response to the appraiser's request from nonce check
- Requested TPM PCR's generated the correct composite from composite check

What the Appraiser Knows

If the PCR composite is correct and includes PCRs 17–20 the appraiser also knows:

PCR	Value	Conclusion
17	$0x00..0 \mid \#$`SINITPolicy`	`SENTER` and `SINIT` ran
18	$0x00..0 \mid \#$`MLE`	`SINIT` measured the MLE
19	$0x00..0 \mid \#$`OS`	OS was correct on startup and was started by MLE
20	$0x00..0 \mid \#$`app`	Application was correct on startup and was started by OS

Initially Good

- Target boot was started by `SENTER`
- Target is built from good parts in correct order

Trust and Secure

Trusted $\neq$ Secure

- The appraiser knows whether it is talking to a good target
- Little information available if the target is bad
- The target is only being observed and not controlled

Protecting Secrets

- Measurement, attestation and appraisal ensure integrity
- Measurement, attestation and appraisal *do not* ensure confidentiality
- Bad systems still run and still do bad things
  - Exfiltrate data
  - Spoof identity and data
  - Denial of service
- TPM data protection can prevent data and keys from bad systems

Protection Mechanisms

- Sealing data to state using a *storage key*
- Binding data to a TPM using a *binding key*
- Integrity checks using NVRAM

Sealing Data to State

Sealing Data

`TPM_Seal` encrypts data for use in conjunction with the local TPM using a *storage key*

- Sealing data to state can involve PCRs, password, and locality
  - PCRs and locality protect data from a bad system
  - passwords protect data from a bad user
- TPM keys are protected by using storage keys
  - Sealing private key to state
  - Installing is unsealing in the TPM
- The SRK is a storage key
  - Used like any other storage key
  - Always installed and can only be reset with `TPM_TakeOwnership`

Sealing Data to State

- Installed storage key for encryption
  - Created by the TPM using `TPM_CreateWrapKey`
  - Can wrap or seal the storage key as well as data
- Password (optional)
  - Called *authdata*
  - Provided by caller during unseal
- PCR values expected for decryption (optional)
  - Which PCRs and their values as composite
  - Will not decrypt if TPM PCRs do not match expected PCRs
- Locality constraints on decryption (optional)
  - Access control like PCR access
  - Must be in locality greater or equal to specified locality

Binding Data to TPM

Binding Data

Binding encrypts data for any TPM using a *binding key*

- Binding is performed outside the TPM
  - Simple encryption using public part of binding key
  - No PCR, locality or authdata constraints
- Unbinding is performed by the TPM
  - TPM key used for encryption must be installed in the TPM
  - Key *can* be sealed to state providing additional protection
- Remember a TPM key's public key is always in the clear
  - Allows for binding away from the TPM
  - Allows for signature checking away from the TPM

Binding Data to TPM

- Binding key for encryption
  - Need not be installed in the target TPM for binding
  - Encryption performed outside the TPM using public key
  - Private key is never exposed during binding
- Bound data is simply encrypted
  - No options for including state or locality
- Binding Key can be protected as any sealed data
  - Sealed to state, locality, authdata
  - Binding key implements enveloping

Using NVRAM

NVRAM

NVRAM is a place to put things before boot for use by TPM and system software

- Minimum size only 1280 bytes
- Limited number of writes and can be burned out
- Access control defined for regions like keys
  - PCR contents, locality, authdata
  - Doesn’t protect anything beyond access control

Using NVRAM

- Stores small data
  - Harder to modify than traditional data on disk or in memory
  - Available for reference checking during operation
- Typical NVRAM contents include:
  - Hashes for integrity checking
  - Trusted public keys for signature checking and encryption
  - Certificates for authentication checks
- Useful for:
  - User-defined sentinel values for trusted boot
  - Initializing Certificate Authority keys or server addresses
  - Hashes of critical software or data for checking during boot
  - Public key for verifying owner signatures
  - Providing resources for early boot

Protecting Data (Redux)

Sealing, Binding and NVRAM

TPM operations provide data protection ranging from simple integrity checks to confidentiality, integrity and system state.

- Check hash of downloaded software or software from disk using NVRAM hash
  - Hash failure implies bad software
- Check signature of downloaded software or software from disk using NVRAM key
  - Signature check failure implies bad software or bad signature
- Seal critical boot/operational data to state
  - Wrong state implies data will not unseal
- Bind transmitted image/data to TPM with sealed key
  - Confidentiality preserved by encryption
  - State ensured by sealed key