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

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.

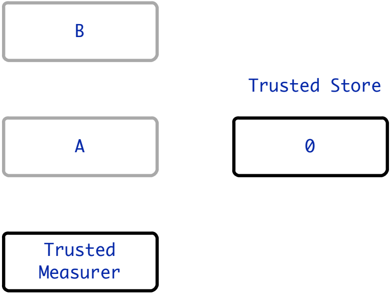
Tools for Trust

- $\#X$ — Hash function such as MD-5
  - $\#X$ 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
  - $[X]_{Y^{-1}}$ is unique for every X and Y pair
  - Guessing $[X]_{Y^{-1}}$ from X is impossible

Measurement — Chaining Evidence

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

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



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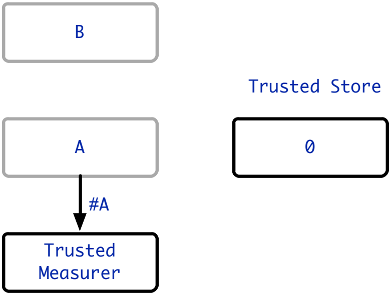

Measurement — Chaining Evidence

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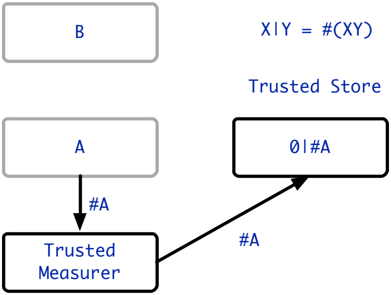

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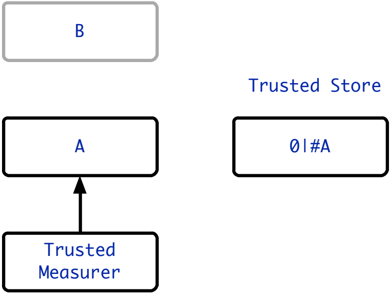
- Launch the new software



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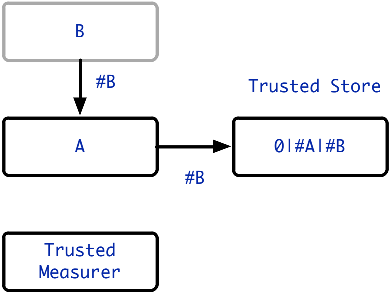
- Launch the new software
- Repeat for each system software component



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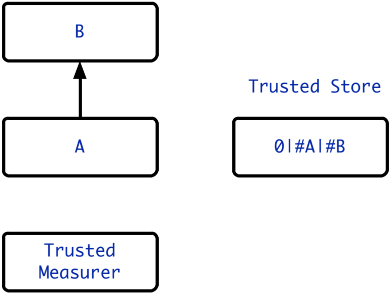


Appraisal — What Do We Know?

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

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

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

Measured Boot gathers evidence of these chains

Trusted Platform Module

The *Trusted Platform Module (TPM)* is a cryptographic coprocessor 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
  - Resettable — Can a PCR be reset
  - Many others that we don’t need yet

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

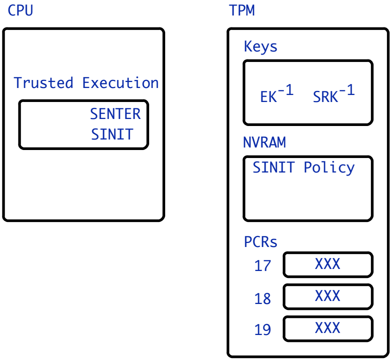
A *Root of Trust for Storage* is trusted to protect stored data

- 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



CPU

Trusted Execution

SENTER

SINIT

TPM

Keys

EK^{-1} SRK^{-1}

NVRAM

SINIT Policy

PCRs

17 XXX

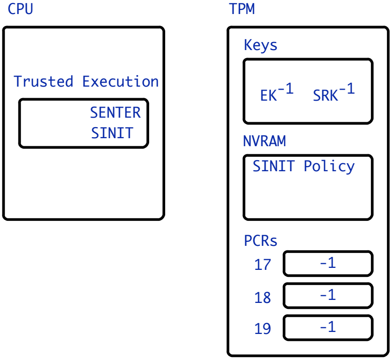
18 XXX

19 XXX

One Step from Roots of Trust

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

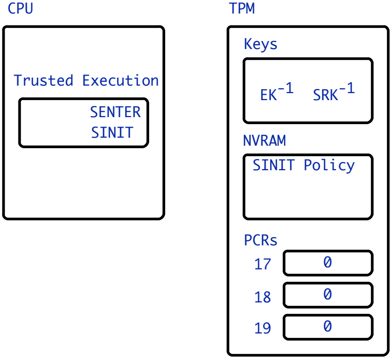
- Power-on reset
- Resettable PCRs set to -1



One Step from Roots of Trust

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

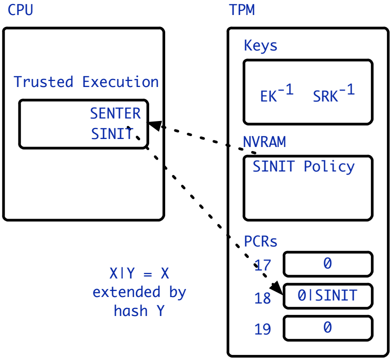
- Power-on reset
- Resettable PCRs set to -1
- `SENTER` called, resets resettable PCRs to 0



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:

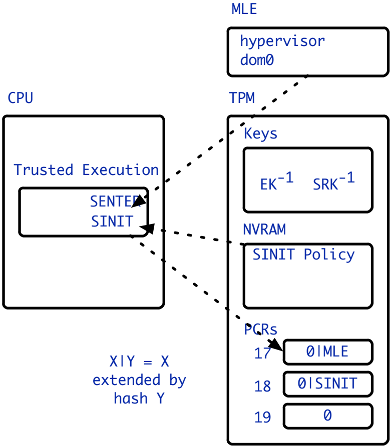
- `SENTER` was called — Resetting PCR 18 starts measurements at 0 rather than -1
- `SINIT` was measured by `SENTER` — Only `SENTER` can extend PCR 18
- `SINIT` uses the correct policy — PCR 18 is extended with `SINIT` measurement policy
- `SENTER` ran before `SINIT` was measured — $A \mid B \neq B \mid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

Measurement $\neq$ Trust

Measurements must be appraised to determine trust.

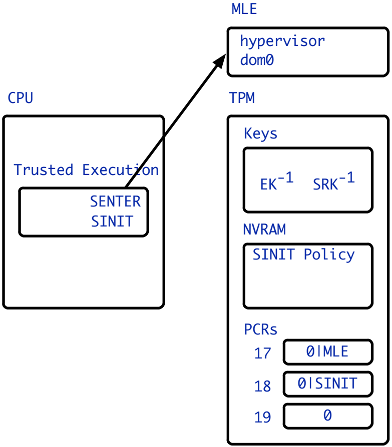
Two Steps from Roots of Trust

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



Two Steps from Roots of Trust

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

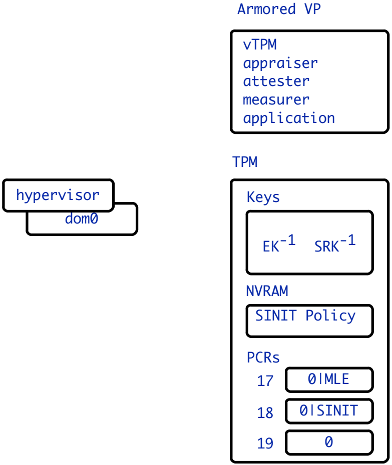


What We Know From Good PCRs

- `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
- Initial OS is good — Measured by good `MLE` into PCR

Boot the MLE

- SENTER starts the MLE
  - SENTER starts the hypervisor
  - SENTER passes dom0 to hypervisor
  - hypervisor starts dom0



hypervisor

dom0

Armored VP

vTPM
appraiser
attester
measurer
application

TPM

Keys

EK^{-1} SRK^{-1}

NVRAM

SINIT Policy

PCRs

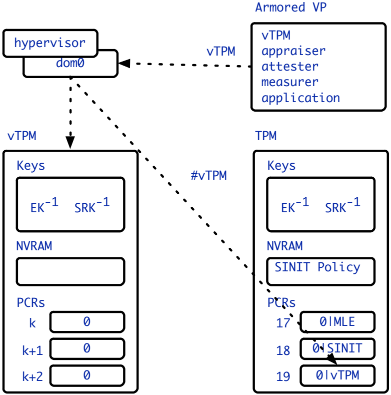
17 0|MLE

18 0|SINIT

19 0

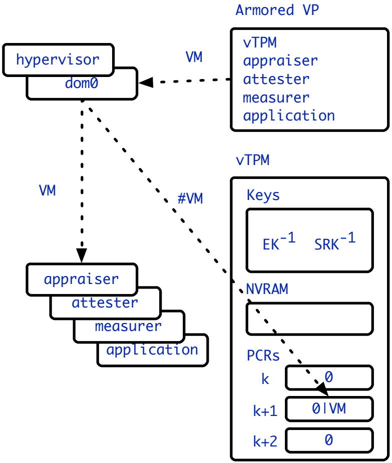
Boot the MLE

- SENTER starts the MLE
  - SENTER starts the hypervisor
  - SENTER passes dom0 to hypervisor
  - hypervisor starts dom0
- dom0 constructs the Armored VP
  - Measures the vTPM into the TPM
  - Starts the vTPM



Boot the MLE

- SENTER starts the MLE
  - SENTER starts the hypervisor
  - SENTER passes dom0 to hypervisor
  - hypervisor starts dom0
- dom0 constructs the Armored VP
  - Measures the vTPM into the TPM
  - Starts the vTPM
  - Measures remaining Armored VMs into the vTPM
  - Starts remaining Armored VMs
  - Measures Armored application into the vTPM
  - Starts the Armored application



Boot the MLE

- SENTER starts the MLE
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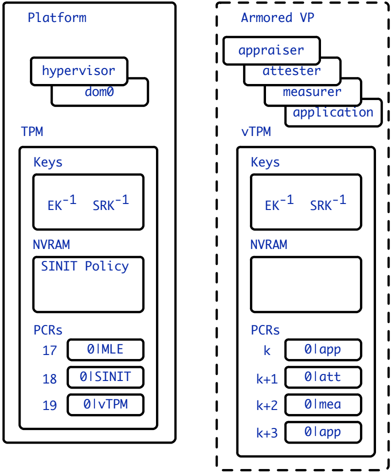
  - hypervisor starts dom0
- dom0 constructs the Armored VP
  - Measures the vTPM into the TPM
  - Starts the vTPM
  - Measures remaining Armored VMs into the vTPM
  - Starts remaining Armored VMs
  - Measures Armored application into the vTPM
  - Starts the Armored application



What we know from good PCRs

- The right hypervisor and dom0 started - PCR 17 measurement and we trust `SENTER`, `SINIT` and `SINIT` Policy
- The right vTPM started - PCR 19 measurement and we trust `SENTER`, `SINIT`, and dom0[2]
- The right ArmoredSoftware components started - vTPM PCRs and we trust dom0 and the vTPM
- The right application started - vTPM PCRs and we trust dom0 and the vTPM

[2] More work for vTPM startup remains

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
  - RTM is the Trusted Measurer
  - RTS is the Trusted Store
  - RTR is the Trusted Reporter (coming soon...)
- 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
- AIK is a wrapped TPM key usable only in the TPM that generated it
  - $wrap(AIK, \{pcr\}) = \langle AIK, seal(AIK^{-1}, \{pcr\}) \rangle$
  - $seal(AIK^{-1}, \{pcr\}) = \{AIK^{-1}\}_{SRK}$ and decrypts only when pcr matches the TPMs PCRs at decryption time
- Generated by the TPM with command `TPM_Quote`

Checking a Quote

Assume that the appraiser is given q of the form:

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

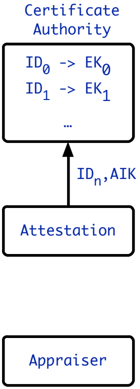
- Signature check using *AIK* — Signature was generated by a TPM with AIK installed
- *pcr* check using regenerated composite from desired PCR values — TPM PCRs matched desired PCR values at quote generation time
- *n* check by knowing nonce or data values — Nonce provides replay prevention. Other data serves other purposes.

The binding of AIK to the target is missing

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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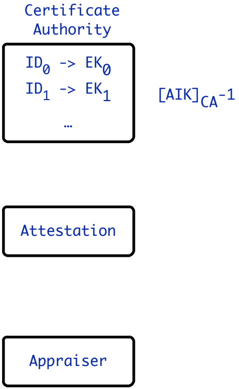

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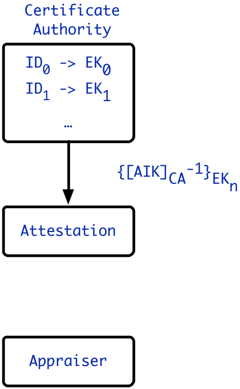
- CA encrypts $[AIK]_{CA^{-1}}$ with ID_n's EK_n



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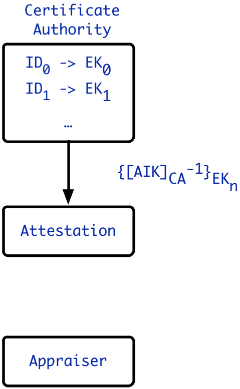
- CA sends $\{[AIK]_{CA^{-1}}\}_{EK_n}$ to ID_n



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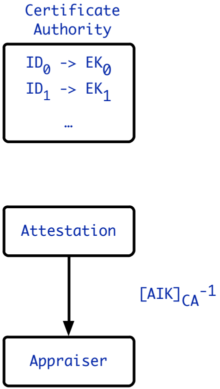
- CA encrypts $[AIK]_{CA^{-1}}$ with ID_n's EK_n
- CA sends $\{[AIK]_{CA^{-1}}\}_{EK_n}$ to ID_n
- ID_n decrypts encrypted AIK with EK_n^{-1}



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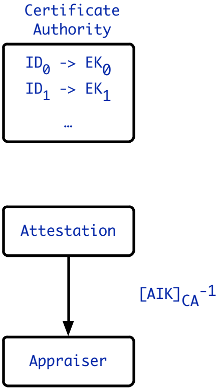
- ID_n requests AIK certification from CA
- CA signs AIK with CA^{-1}
- CA encrypts $[AIK]_{CA^{-1}}$ with ID_n's EK_n
- CA sends $\{[AIK]_{CA^{-1}}\}_{EK_n}$ to ID_n
- ID_n decrypts encrypted AIK with EK_n^{-1}
- ID_n sends $[AIK]_{CA^{-1}}$ to appraiser



Using Protocol Notation

Protocol notation specifies communication:

$$Sender \rightarrow Receiver : Messsage$$

Key Certification Protocol

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

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