Trust

What it is and how to get it

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

- 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.

- $\#X$ — 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

- $(X, \{X^{-1}\}_{Y^{-1}})$ — 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 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

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

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

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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

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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

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Chaining Measurement — Gathering Evidence

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

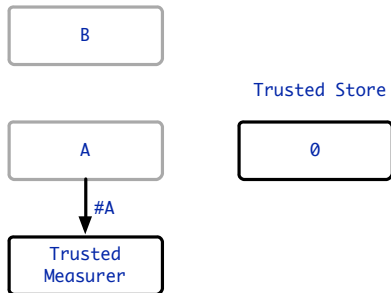▶ Start with a root measurer and
  store that are trusted *a priori*

B

Trusted Store

A		0
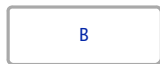
Trusted Measurer

Chaining Measurement — Gathering Evidence

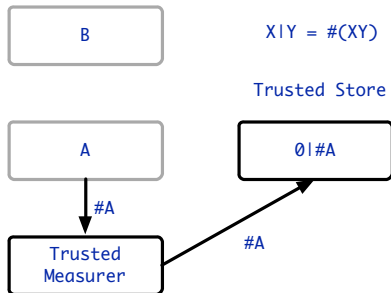We would like to start *A* and *B* while gathering evidence for determining trust

- ▶ Start with a root measurer and store that are trusted *a priori*
- ▶ Measure the new software to be launched

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*
- ► Measure the new software to be launched
- ► Store the measurement of the new software

Chaining Measurement — Gathering Evidence

We would like to start *A* and *B* while gathering evidence for determining trust
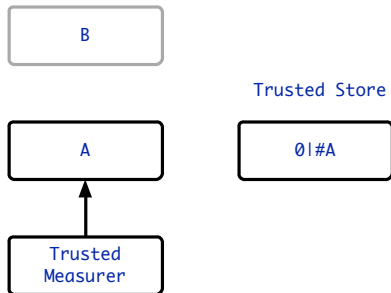
- ▶ Start with a root measurer and store that are trusted *a priori*
- ▶ Measure the new software to be launched
- ▶ Store the measurement of the new software
- ▶ Launch the new software

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*
- Measure the new software to be launched
- Store the measurement of the new software
- Launch the new software
- Repeat for each system software component

Chaining Measurement — Gathering Evidence

We would like to start *A* and *B* while gathering evidence for determining trust
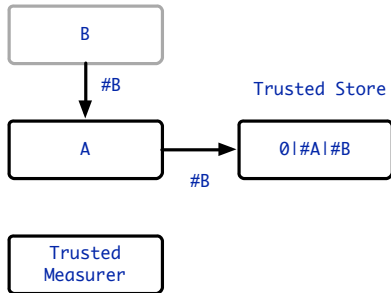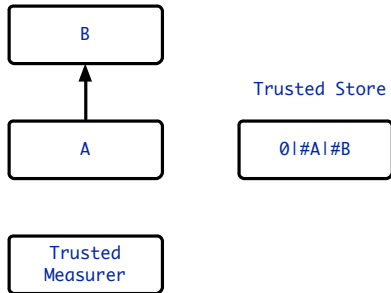
- ▶ Start with a root measurer and store that are trusted *a priori*
- ▶ Measure the new software to be launched
- ▶ Store the measurement of the new software
- ▶ Launch the new software
- ▶ Repeat for each system software component

```
      ┌──────────────┐
      │      B       │
      └──────────────┘               Trusted Store
             ▲
             │                        ┌──────────────┐
      ┌──────────────┐                │  0|#A|#B     │
      │      A       │                └──────────────┘
      └──────────────┘


      ┌──────────────┐
      │   Trusted    │
      │   Measurer   │
      └──────────────┘
```

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

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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...

$T^x[y]$ is an homogeneous relation over actors that is true when *x trusts y*. $T^x[y]$ is by definition a preorer:

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

Measured Boot gathers evidence to check trust relationships.

A *chain of trust* from X_0 to X_n:

$$T^{X_0}[X_1] \wedge T^{X_1}[X_2] \wedge \ldots \wedge T^{X_{n-1}}[X_n]$$

- 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

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

- 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

- 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

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)

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
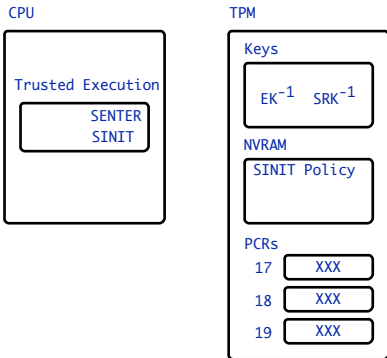- Linking EK to its platform is done by a trusted Certificate Authority (CA)

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

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

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

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

CPU

Trusted Execution
SENTER
SINIT

TPM

Keys

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

NVRAM
SINIT Policy

PCRs
17 -1
18 -1
19 -1

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

- ► Power-on reset
- ► Resettable PCRs set to -1
- ► SENTER called, resets
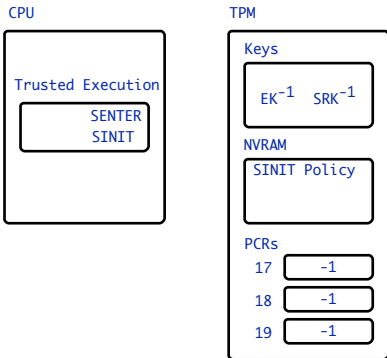 resettable PCRs to 0
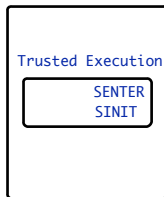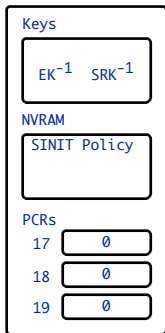
Roots of trust are used to build a trusted system from boot.

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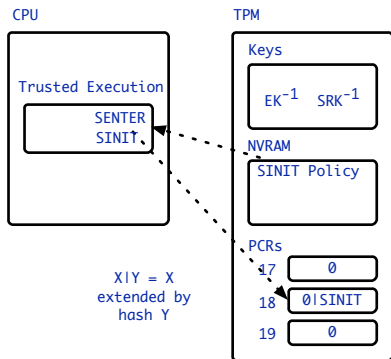
CPU

Trusted Execution

SENTER
SINIT

X|Y = X
extended by
hash Y

TPM

Keys

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

NVRAM

SINIT Policy

PCRs

17   0

18   0|SINIT

19   0

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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.

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

MLE

Initial Image

CPU

Trusted Execution

SENTER
SINIT

TPM

Keys

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

NVRAM

SINIT Policy

PCRs

17   0|MLE

18   0|SINIT

19   0

X|Y = X
extended by
hash Y

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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

MLE

Initial Image

CPU

Trusted Execution

SENTER
SINIT

TPM

Keys

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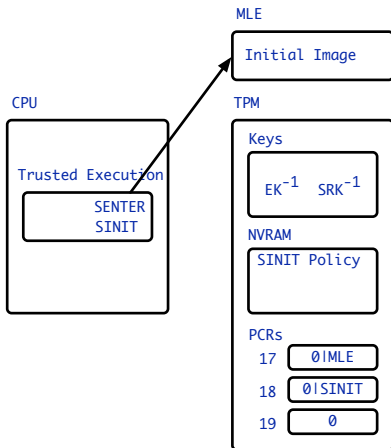
NVRAM

SINIT Policy

PCRs

17   0|MLE

18   0|SINIT

19   0

- `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.

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

Operating System

```
kernel
file system
drivers
run-time trust
applications
```

TPM

```
initial image
```

Keys

$$EK^{-1} \quad SRK^{-1}$$

NVRAM

```
SINIT Policy
```

PCRs

17	0	MLE
18	0	SINIT
19	0

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- 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

▶ 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
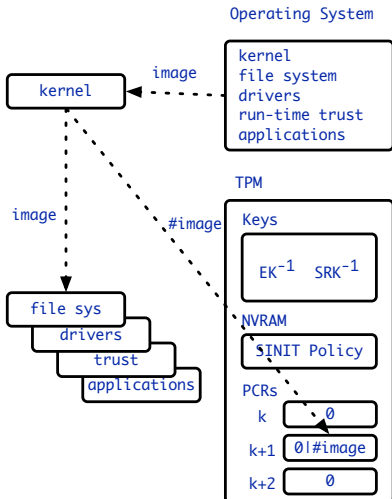 ▶ Measures application into the TPM
  ▶ Starts the application

- `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
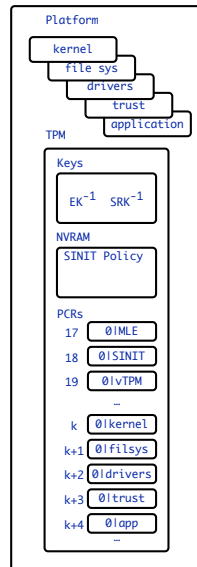- Kernel boots the system
  - Measures remaining images into the TPM
  - Starts remaining images
  - Measures application into the TPM
  - Starts the application

Platform

kernel
file sys
drivers
trust
application

TPM

Keys

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

NVRAM

SINIT Policy

PCRs

17 0|MLE
18 0|SINIT
19 0|vTPM
...
k 0|kernel
k+1 0|filsys
k+2 0|drivers
k+3 0|trust
k+4 0|app
...

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

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- ▶ 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

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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

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

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

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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

```
        Certificate
         Authority
  ┌───────────────────┐
  │ ID_0 -> EK_0      │
  │ ID_1 -> EK_1      │
  │      …            │
  └───────────────────┘
           ▲
           │ ID_n,AIK
  ┌───────────────────┐
  │ Attestation       │
  └───────────────────┘


  ┌───────────────────┐
  │ Appraiser         │
  └───────────────────┘
```
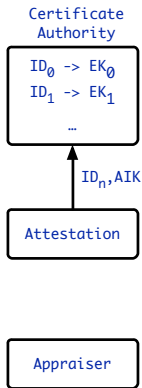
Assume a trusted Certificate Authority (CA) that maintains links from ID to *EK* with well-known public key *CA*

- ID_n requests *AIK* certification from CA
- CA signs *AIK* with CA^{-1}

```
 Certificate
  Authority

 ID₀ -> EK₀
 ID₁ -> EK₁         [AIK]_CA^-1
    …
```

```
 Attestation
```

```
 Appraiser
```

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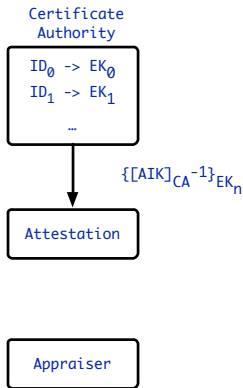
Assume a trusted Certificate Authority (CA) that maintains links from ID to *EK* with well-known public key *CA*

- ID_n requests *AIK* certification from CA
- CA signs *AIK* with CA^{-1}
- CA encrypts $[AIK]_{CA^{-1}}$ with ID_n's EK_n

```
Certificate
 Authority
┌─────────────────┐
│ ID₀ -> EK₀      │
│ ID₁ -> EK₁      │
│                 │
│     …           │
└─────────────────┘
         │
         │        {[AIK]_CA^-1}_EK_n
         ▼
┌─────────────────┐
│  Attestation    │
└─────────────────┘


┌─────────────────┐
│   Appraiser     │
└─────────────────┘
```
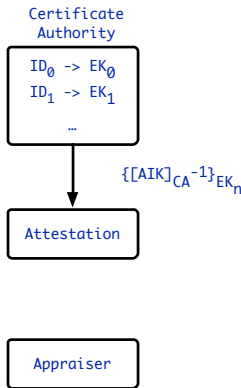
Certifying AIK

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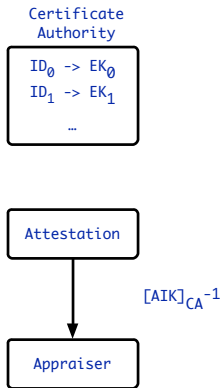- CA sends $\{[AIK]_{CA^{-1}}\}_{EK_n}$ to *ID_n*

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
- 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}*

```
Certificate
 Authority
 ID₀ -> EK₀
 ID₁ -> EK₁
    …
```

```
Attestation
```

$[AIK]_{CA}{}^{-1}$

```
Appraiser
```

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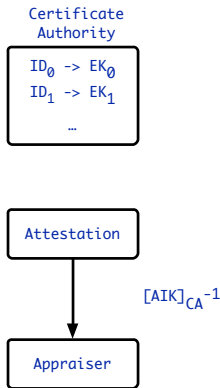The University of Kansas

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
- 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

Certificate Authority

$ID_0 \rightarrow EK_0$
$ID_1 \rightarrow EK_1$
…

Attestation

$[AIK]_{CA}{}^{-1}$

Appraiser

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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

Protocol notation specifies communication:

$$Sender \rightarrow Receiver : Messsage$$

Key Certification Protocol

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

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

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

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 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

- ▶ 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

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

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

- 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

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

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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

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- 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

- 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

- 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

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- 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

- 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

- On initial measurement after startup
  - `SENTER` and `SINIT` ran
  - `SINIT` measured the MLE
  - MLE was correct on startup
- On measurement after application startup
  - OS was correct on startup and was started by MLE
  - Application was correct on startup and was started by OS

Trusted $\neq$ Secure

- The Appraiser knows what it is talking to
- Nothing is protected