Demystifying Attestation in Intel Trust Domain Extensions (TDX) via Formal Verification

Muhammad Usama Sardar and Christof Fetzer
Ack: Anna Galanou, Amna Shahab, Bruno Blanchet
Funding: CPEC, CeTI

Chair of Systems Engineering
Institute of Systems Architecture
Technische Universität Dresden

Dresden, Germany

April 23, 2022

Promise of talk

- Need of logic in an emerging and important domain

Promise of talk

- Need of logic in an emerging and important domain
- CCC: more marketing than scientific[1,2] (highlights only)

[1] Confidential Computing Consortium, *Whitepaper feedback from Muhammad Usama Sardar, Issue #77*, 2020

[2] Sardar and Fetzer, *Confidential Computing and Related Technologies : A Review*, 2021

Promise of talk

- Need of logic in an emerging and important domain
- CCC: more marketing than scientific[1,2] (highlights only)
  - Attestation: one of the most critical and essential parts of TEE

[1]Confidential Computing Consortium, *Whitepaper feedback from Muhammad Usama Sardar, Issue #77*, 2020

[2]Sardar and Fetzer, *Confidential Computing and Related Technologies : A Review*, 2021

Promise of talk

- Need of logic in an emerging and important domain
- CCC: more marketing than scientific[1,2] (highlights only)
  - Attestation: one of the most critical and essential parts of TEE
- Complexity is the worst enemy of security (B. Schneier)

[1] Confidential Computing Consortium, *Whitepaper feedback from Muhammad Usama Sardar, Issue #77*, 2020

[2] Sardar and Fetzer, *Confidential Computing and Related Technologies : A Review*, 2021

Promise of talk

- Need of logic in an emerging and important domain
- CCC: more marketing than scientific[1,2] (highlights only)
  - Attestation: one of the most critical and essential parts of TEE
- Complexity is the worst enemy of security (B. Schneier)
  - Complexity is the best friend of Intel!

[1] Confidential Computing Consortium, *Whitepaper feedback from Muhammad Usama Sardar, Issue #77*, 2020

[2] Sardar and Fetzer, *Confidential Computing and Related Technologies : A Review*, 2021

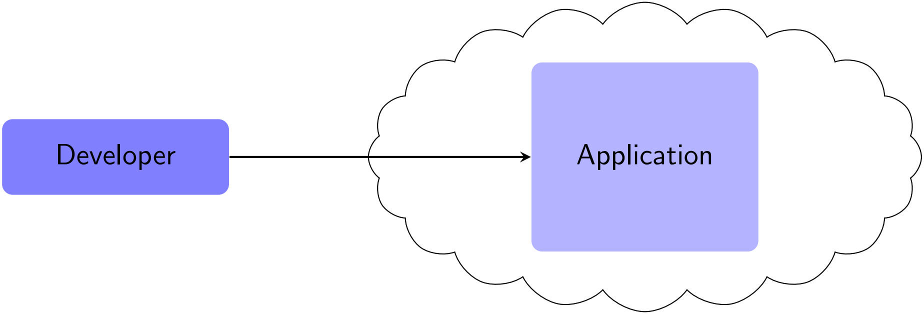
Outline

CC in Public Cloud Scenario

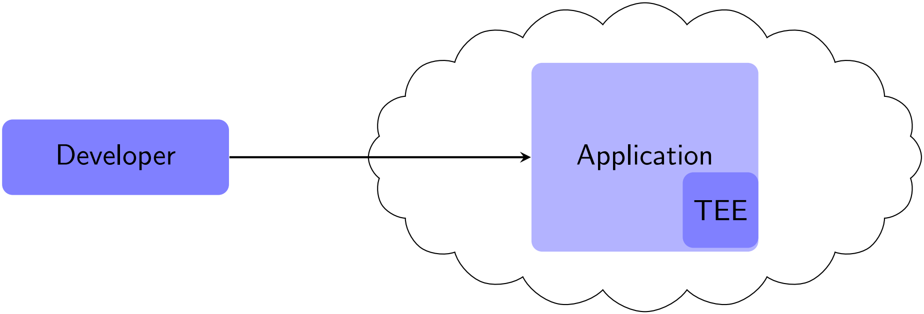
CC in Public Cloud Scenario

Developer

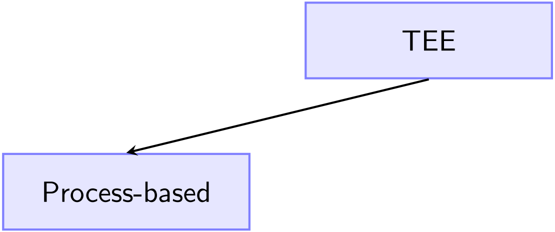
CC in Public Cloud Scenario



CC in Public Cloud Scenario

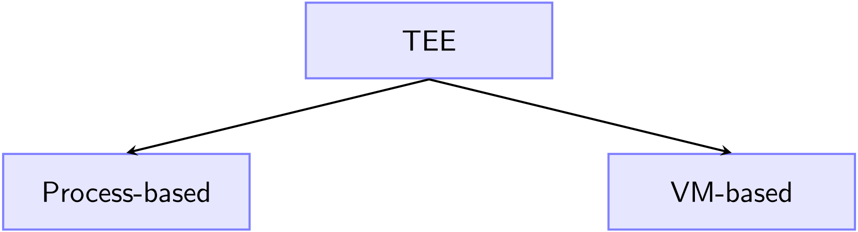


TEEs Granularity (Public cloud commercial solutions)



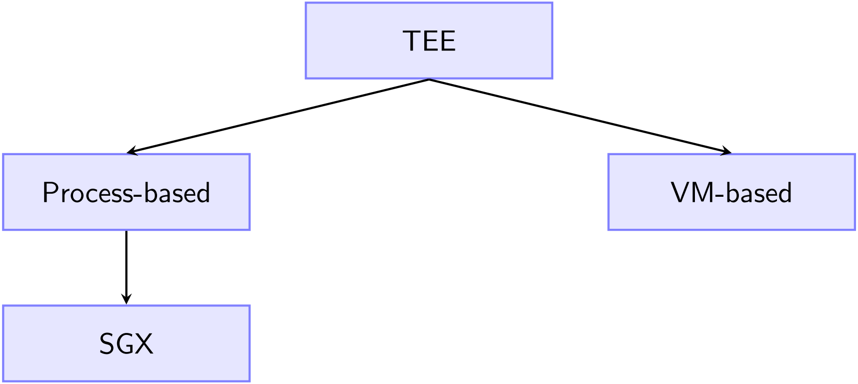
- Smaller TCB

TEEs Granularity (Public cloud commercial solutions)

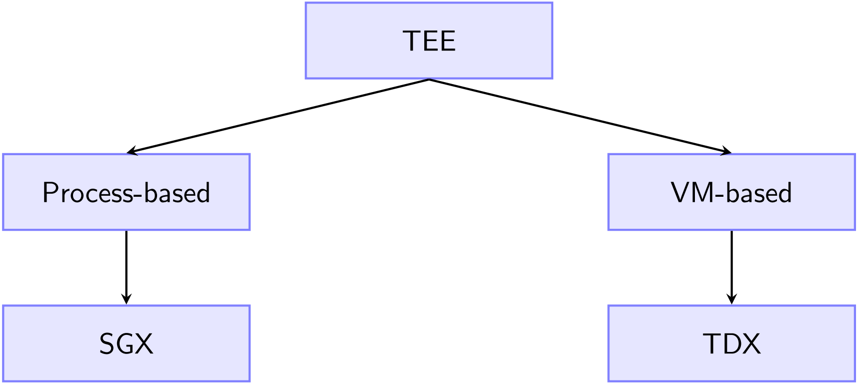


- Ease of use

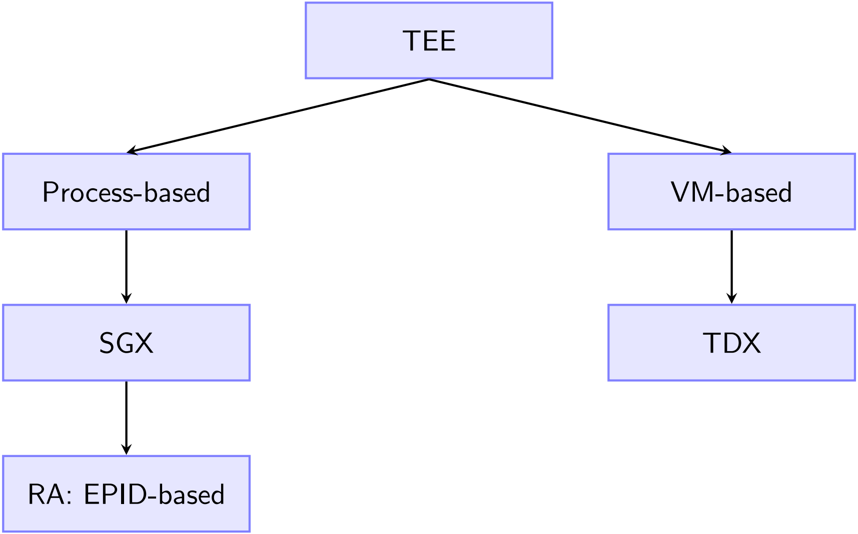
TEEs Granularity (Public cloud commercial solutions)



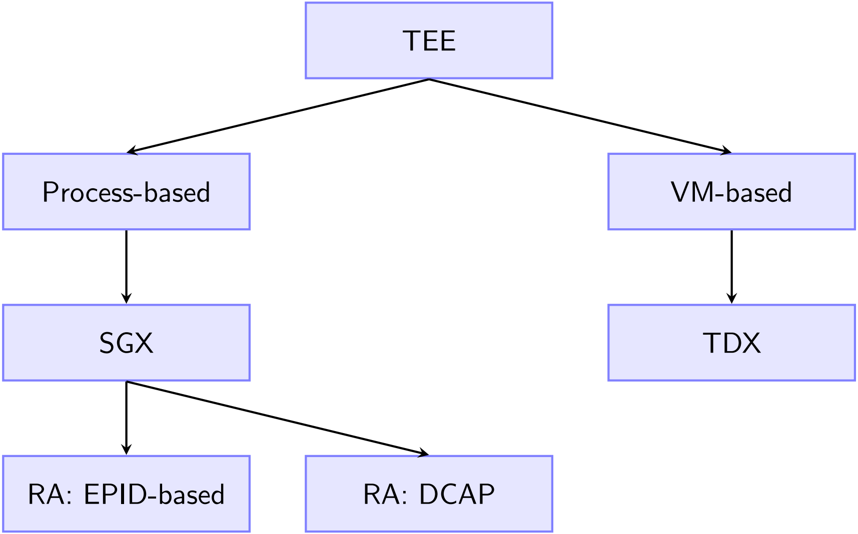
TEEs Granularity (Public cloud commercial solutions)



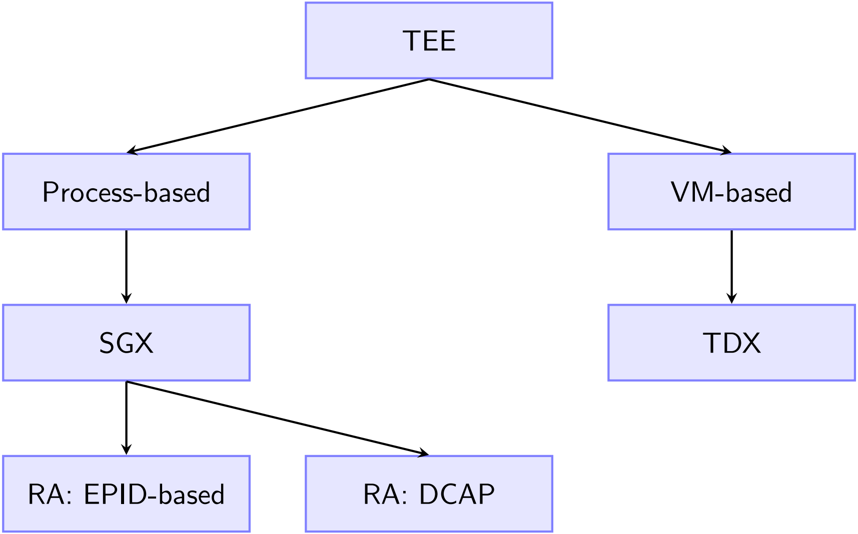
TEEs Granularity (Public cloud commercial solutions)



TEEs Granularity (Public cloud commercial solutions)



TEEs Granularity (Public cloud commercial solutions)



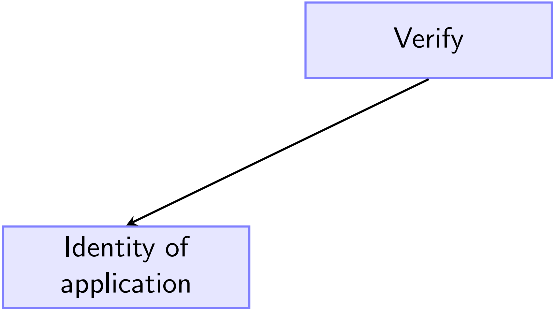
- Different report generation mechanism
- Runtime TD measurements

Attestation

- Trust to developer: right app in right platform

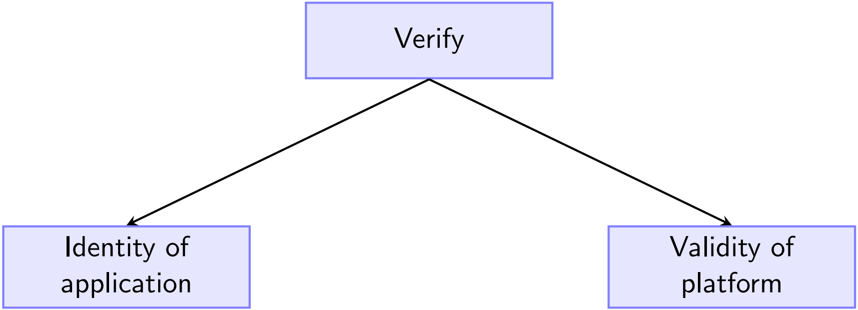
Attestation

- Trust to developer: right app in right platform



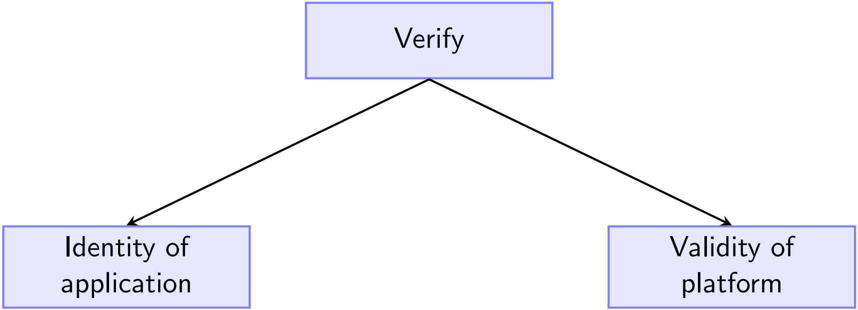
Attestation

- Trust to developer: right app in right platform



Attestation

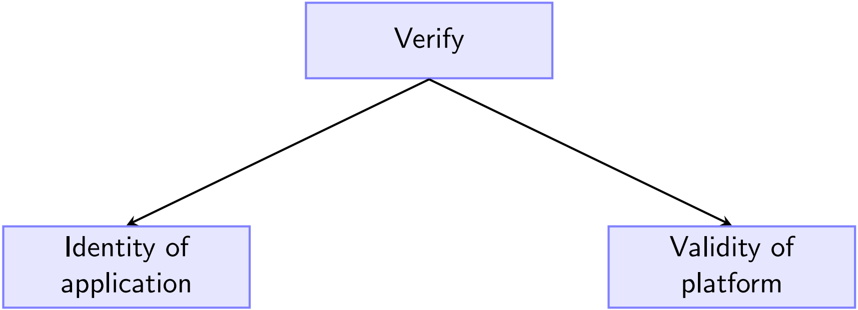
- Trust to developer: right app in right platform



- Secure channel creation

Attestation

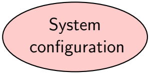
- Trust to developer: right app in right platform



- Secure channel creation
- Importance $\rightarrow$ Provisioning of secrets and config.

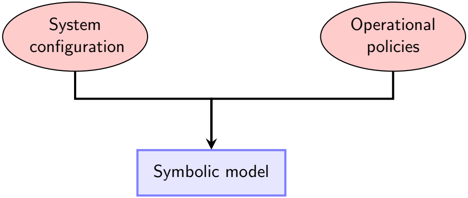
Outline

Workflow of the Analysis Approach

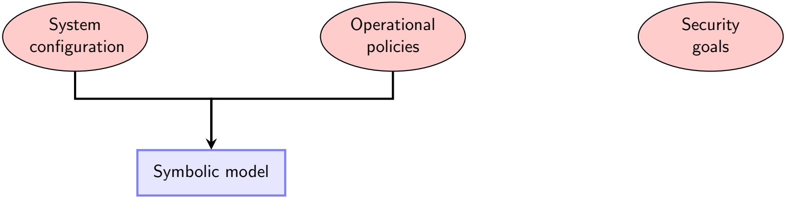


Workflow of the Analysis Approach

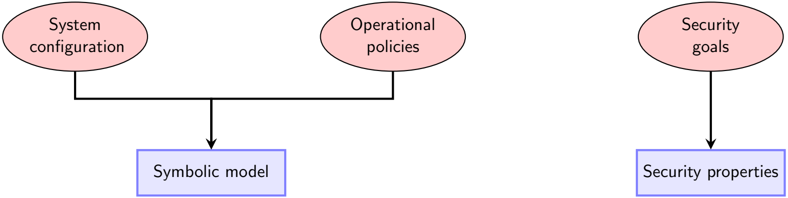
Workflow of the Analysis Approach



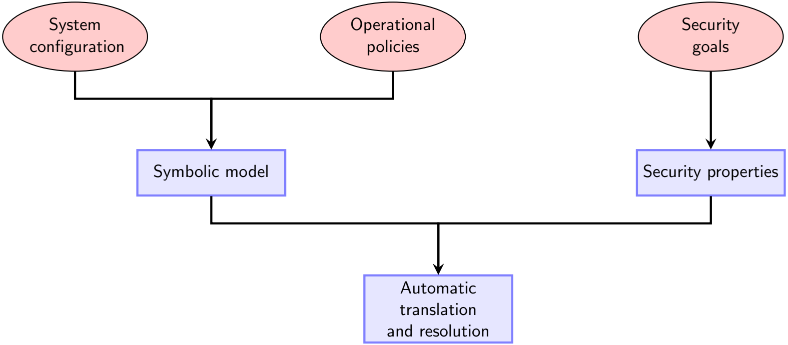
Workflow of the Analysis Approach



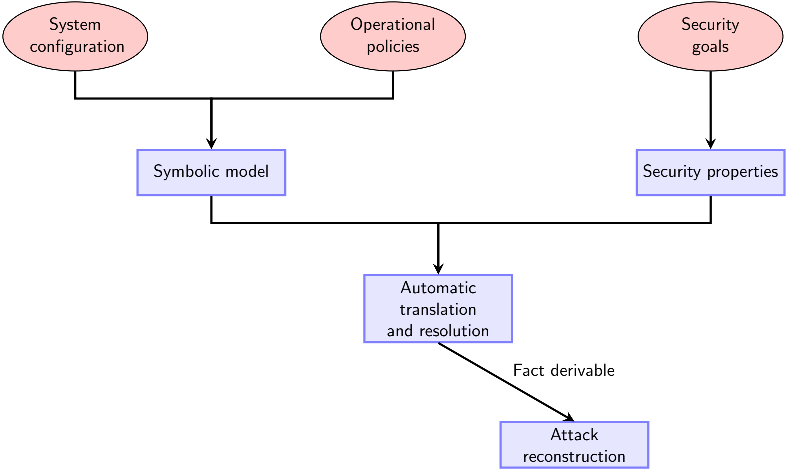
Workflow of the Analysis Approach



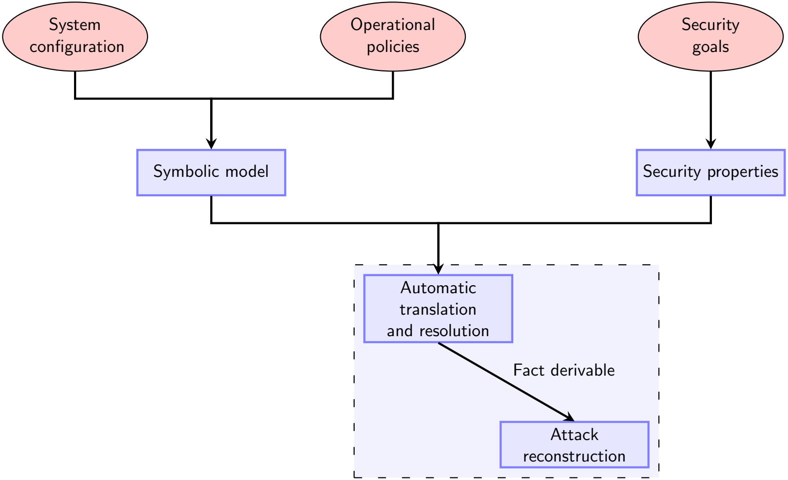
Workflow of the Analysis Approach



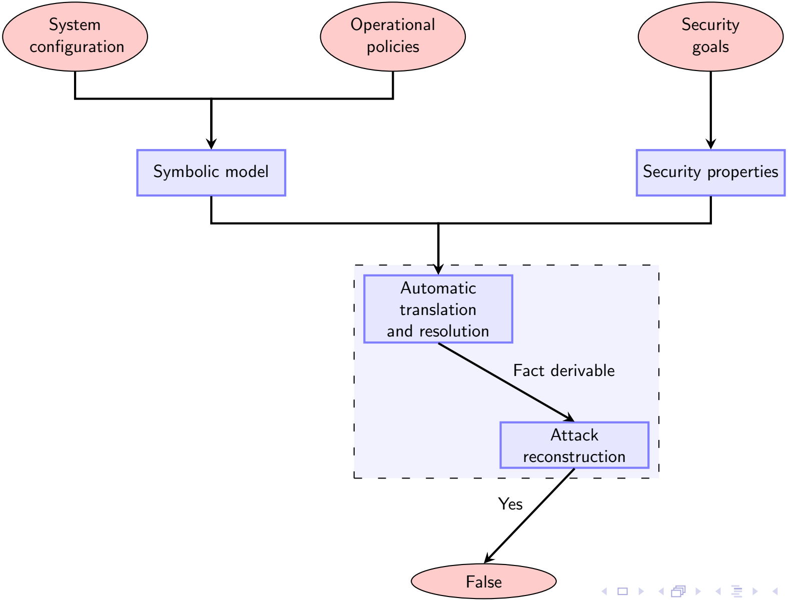
Workflow of the Analysis Approach



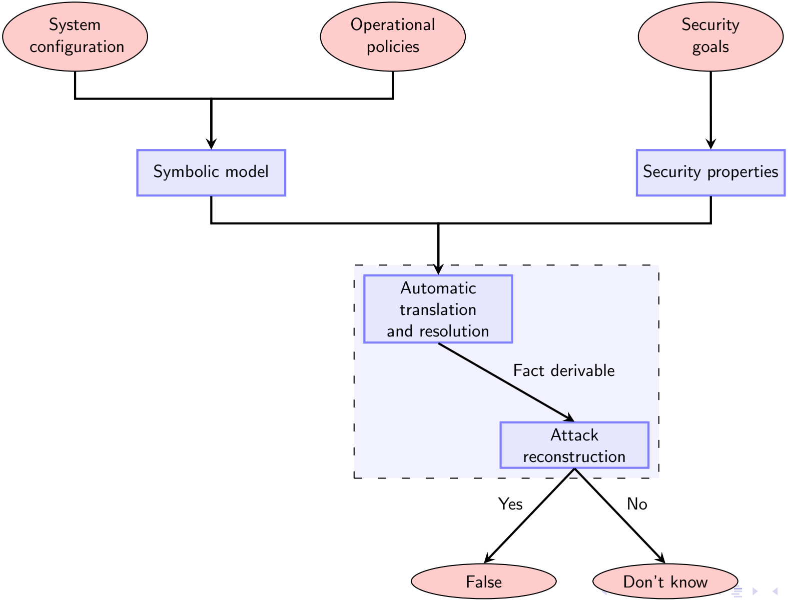
Workflow of the Analysis Approach



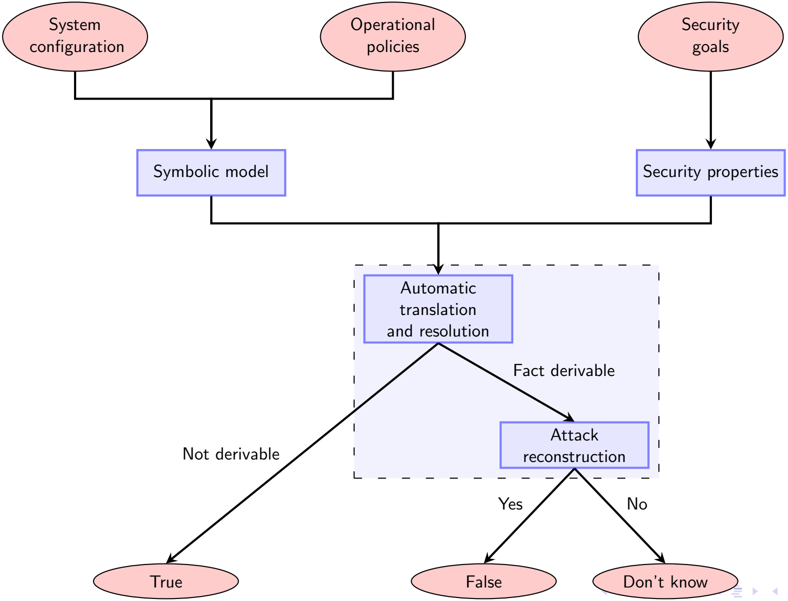
Workflow of the Analysis Approach



Workflow of the Analysis Approach



Workflow of the Analysis Approach



Inference System and Horn Clauses (Simplified)

- Composition rules

Inference System and Horn Clauses (Simplified)

- Composition rules
  - pair $\frac{x \quad y}{\langle x,y \rangle}$ $\quad att(x) \bigwedge att(y) \rightarrow att(\langle x, y \rangle)$

Inference System and Horn Clauses (Simplified)

- Composition rules
  - pair $\frac{x \quad y}{\langle x,y \rangle}$ $\quad att(x) \bigwedge att(y) \rightarrow att(\langle x, y \rangle)$
  - hash $\frac{m}{h(m)}$ $\quad att(m) \rightarrow att(h(m))$

Inference System and Horn Clauses (Simplified)

- Composition rules
  - pair $\frac{x \quad y}{\langle x,y \rangle}$ $\quad att(x) \bigwedge att(y) \rightarrow att(\langle x, y \rangle)$
  - hash $\frac{m}{h(m)}$ $\quad att(m) \rightarrow att(h(m))$
  - hmac $\frac{mk \quad m}{hmac(mk,m)}$ $\quad att(mk) \bigwedge att(m) \rightarrow att(hmac(mk, m))$

Inference System and Horn Clauses (Simplified)

- Composition rules
  - pair $\frac{x \quad y}{\langle x,y \rangle}$ $\quad att(x) \bigwedge att(y) \rightarrow att(\langle x, y \rangle)$
  - hash $\frac{m}{h(m)}$ $\quad att(m) \rightarrow att(h(m))$
  - hmac $\frac{mk \quad m}{hmac(mk,m)}$ $\quad att(mk) \bigwedge att(m) \rightarrow att(hmac(mk, m))$
  - senc $\frac{sek \quad m}{senc(sek,m)}$ $\quad att(sek) \bigwedge att(m) \rightarrow att(senc(sek, m))$

Inference System and Horn Clauses (Simplified)

- Composition rules
  - pair $\frac{x \quad y}{\langle x,y \rangle}$ $\quad att(x) \bigwedge att(y) \rightarrow att(\langle x, y \rangle)$
  - hash $\frac{m}{h(m)}$ $\quad att(m) \rightarrow att(h(m))$
  - hmac $\frac{mk \quad m}{hmac(mk,m)}$ $\quad att(mk) \bigwedge att(m) \rightarrow att(hmac(mk, m))$
  - senc $\frac{sek \quad m}{senc(sek,m)}$ $\quad att(sek) \bigwedge att(m) \rightarrow att(senc(sek, m))$
  - aenc $\frac{aek \quad m}{aenc(aek,m)}$ $\quad att(aek) \bigwedge att(m) \rightarrow att(aenc(aek, m))$

Inference System and Horn Clauses (Simplified)

- Composition rules
  - pair $\frac{x \quad y}{\langle x,y \rangle}$ $\quad att(x) \bigwedge att(y) \rightarrow att(\langle x, y \rangle)$
  - hash $\frac{m}{h(m)}$ $\quad att(m) \rightarrow att(h(m))$
  - hmac $\frac{mk \quad m}{hmac(mk,m)}$ $\quad att(mk) \bigwedge att(m) \rightarrow att(hmac(mk, m))$
  - senc $\frac{sek \quad m}{senc(sek,m)}$ $\quad att(sek) \bigwedge att(m) \rightarrow att(senc(sek, m))$
  - aenc $\frac{aek \quad m}{aenc(aek,m)}$ $\quad att(aek) \bigwedge att(m) \rightarrow att(aenc(aek, m))$
  - sign $\frac{sk \quad m}{signAppDet(sk,m)}$ $\quad att(sk) \bigwedge att(m) \rightarrow att(signAppDet(sk, m))$

Inference System and Horn Clauses (Simplified)

- Composition rules
  - pair $\frac{x \quad y}{\langle x,y \rangle}$ $\quad att(x) \bigwedge att(y) \rightarrow att(\langle x, y \rangle)$
  - hash $\frac{m}{h(m)}$ $\quad att(m) \rightarrow att(h(m))$
  - hmac $\frac{mk \quad m}{hmac(mk,m)}$ $\quad att(mk) \bigwedge att(m) \rightarrow att(hmac(mk, m))$
  - senc $\frac{sek \quad m}{senc(sek,m)}$ $\quad att(sek) \bigwedge att(m) \rightarrow att(senc(sek, m))$
  - aenc $\frac{aek \quad m}{aenc(aek,m)}$ $\quad att(aek) \bigwedge att(m) \rightarrow att(aenc(aek, m))$
  - sign $\frac{sk \quad m}{signAppDet(sk,m)}$ $\quad att(sk) \bigwedge att(m) \rightarrow att(signAppDet(sk, m))$
- Decomposition rules

Inference System and Horn Clauses (Simplified)

- Composition rules
  - pair $\frac{x \quad y}{\langle x,y \rangle}$ $\quad att(x) \bigwedge att(y) \rightarrow att(\langle x, y \rangle)$
  - hash $\frac{m}{h(m)}$ $\quad att(m) \rightarrow att(h(m))$
  - hmac $\frac{mk \quad m}{hmac(mk,m)}$ $\quad att(mk) \bigwedge att(m) \rightarrow att(hmac(mk, m))$
  - senc $\frac{sek \quad m}{senc(sek,m)}$ $\quad att(sek) \bigwedge att(m) \rightarrow att(senc(sek, m))$
  - aenc $\frac{aek \quad m}{aenc(aek,m)}$ $\quad att(aek) \bigwedge att(m) \rightarrow att(aenc(aek, m))$
  - sign $\frac{sk \quad m}{signAppDet(sk,m)}$ $\quad att(sk) \bigwedge att(m) \rightarrow att(signAppDet(sk, m))$
- Decomposition rules
  - projection $\frac{\langle x,y \rangle}{x}$, $\frac{\langle x,y \rangle}{y}$ $\quad att(\langle x, y \rangle) \rightarrow att(x),\ att(\langle x, y \rangle) \rightarrow att(y)$

Inference System and Horn Clauses (Simplified)

- Composition rules
  - pair $\frac{x \quad y}{\langle x,y \rangle}$ $\quad att(x) \bigwedge att(y) \rightarrow att(\langle x, y \rangle)$
  - hash $\frac{m}{h(m)}$ $\quad att(m) \rightarrow att(h(m))$
  - hmac $\frac{mk \quad m}{hmac(mk,m)}$ $\quad att(mk) \bigwedge att(m) \rightarrow att(hmac(mk, m))$
  - senc $\frac{sek \quad m}{senc(sek,m)}$ $\quad att(sek) \bigwedge att(m) \rightarrow att(senc(sek, m))$
  - aenc $\frac{aek \quad m}{aenc(aek,m)}$ $\quad att(aek) \bigwedge att(m) \rightarrow att(aenc(aek, m))$
  - sign $\frac{sk \quad m}{signAppDet(sk,m)}$ $\quad att(sk) \bigwedge att(m) \rightarrow att(signAppDet(sk, m))$
- Decomposition rules
  - projection $\frac{\langle x,y \rangle}{x}$, $\frac{\langle x,y \rangle}{y}$ $\quad att(\langle x, y \rangle) \rightarrow att(x),\ att(\langle x, y \rangle) \rightarrow att(y)$
  - sdec $\frac{sek \quad senc(sek,m)}{m}$ $\quad att(sek) \bigwedge att(senc(sek, m)) \rightarrow att(m)$

Inference System and Horn Clauses (Simplified)

- Composition rules
  - pair $\frac{x \quad y}{\langle x,y\rangle}$ $\quad att(x) \bigwedge att(y) \rightarrow att(\langle x, y\rangle)$
  - hash $\frac{m}{h(m)}$ $\quad att(m) \rightarrow att(h(m))$
  - hmac $\frac{mk \quad m}{hmac(mk,m)}$ $\quad att(mk) \bigwedge att(m) \rightarrow att(hmac(mk, m))$
  - senc $\frac{sek \quad m}{senc(sek,m)}$ $\quad att(sek) \bigwedge att(m) \rightarrow att(senc(sek, m))$
  - aenc $\frac{aek \quad m}{aenc(aek,m)}$ $\quad att(aek) \bigwedge att(m) \rightarrow att(aenc(aek, m))$
  - sign $\frac{sk \quad m}{signAppDet(sk,m)}$ $\quad att(sk) \bigwedge att(m) \rightarrow att(signAppDet(sk, m))$
- Decomposition rules
  - projection $\frac{\langle x,y\rangle}{x}$, $\frac{\langle x,y\rangle}{y}$ $\quad att(\langle x, y\rangle) \rightarrow att(x),\ att(\langle x, y\rangle) \rightarrow att(y)$
  - sdec $\frac{sek \quad senc(sek,m)}{m}$ $\quad att(sek) \bigwedge att(senc(sek, m)) \rightarrow att(m)$
  - adec $\frac{adk \quad aenc(pk(adk),m)}{m}$
    $att(adk) \bigwedge att(aenc(pk(adk), m)) \rightarrow att(m)$

Inference System and Horn Clauses (Simplified)

- Composition rules
  - pair $\frac{x \quad y}{\langle x,y \rangle}$ $\quad att(x) \bigwedge att(y) \rightarrow att(\langle x, y \rangle)$
  - hash $\frac{m}{h(m)}$ $\quad att(m) \rightarrow att(h(m))$
  - hmac $\frac{mk \quad m}{hmac(mk,m)}$ $\quad att(mk) \bigwedge att(m) \rightarrow att(hmac(mk, m))$
  - senc $\frac{sek \quad m}{senc(sek,m)}$ $\quad att(sek) \bigwedge att(m) \rightarrow att(senc(sek, m))$
  - aenc $\frac{aek \quad m}{aenc(aek,m)}$ $\quad att(aek) \bigwedge att(m) \rightarrow att(aenc(aek, m))$
  - sign $\frac{sk \quad m}{signAppDet(sk,m)}$ $\quad att(sk) \bigwedge att(m) \rightarrow att(signAppDet(sk, m))$
- Decomposition rules
  - projection $\frac{\langle x,y \rangle}{x}$, $\frac{\langle x,y \rangle}{y}$ $\quad att(\langle x, y \rangle) \rightarrow att(x),\ att(\langle x, y \rangle) \rightarrow att(y)$
  - sdec $\frac{sek \quad senc(sek,m)}{m}$ $\quad att(sek) \bigwedge att(senc(sek, m)) \rightarrow att(m)$
  - adec $\frac{adk \quad aenc(pk(adk),m)}{m}$
    $att(adk) \bigwedge att(aenc(pk(adk), m)) \rightarrow att(m)$
  - verifysign $\frac{vpk(sk) \quad m \quad signAppDet(sk,m)}{true}$

Outline

1. Introduction
2. Formal Security Analysis Approach
3. TDX
   - Formal Specification
   - Discrepancies Identified
   - Automated Verification
4. Summary

Contributions

- Precise specification in ProVerif[3]

[3] Blanchet et al., "Modeling and verifying security protocols with the applied pi calculus and ProVerif", 2016

Contributions

- Precise specification in ProVerif[3]
- Identification of discrepancies

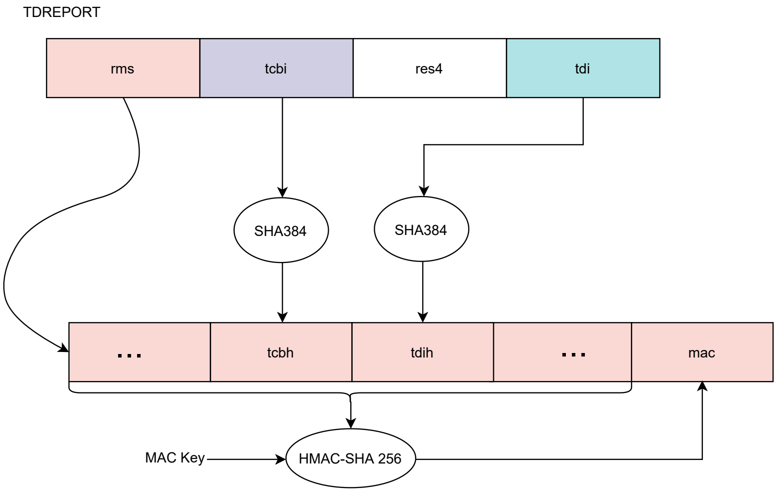
[3] Blanchet et al., "Modeling and verifying security protocols with the applied pi calculus and ProVerif", 2016

Contributions

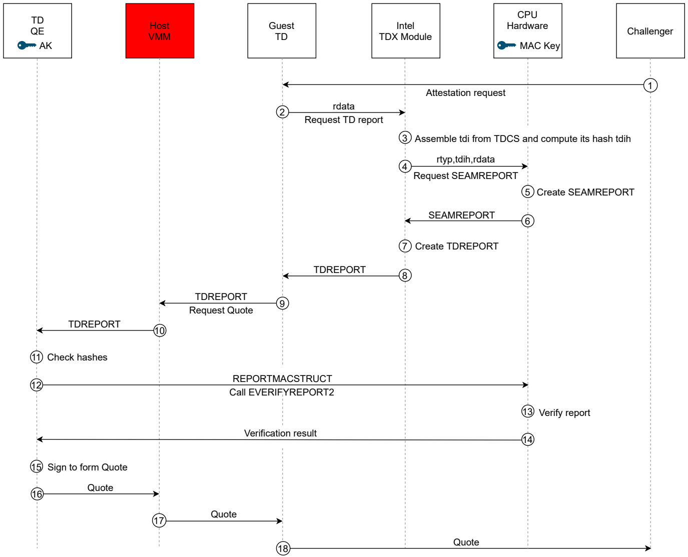
- Precise specification in ProVerif[3]
- Identification of discrepancies
- Automated verification of properties in ProVerif

[3] Blanchet et al., "Modeling and verifying security protocols with the applied pi calculus and ProVerif", 2016

TD Report Structures (Simplified view)

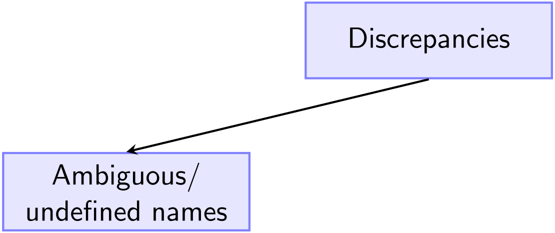


TDX Attestation Flow for Quote Generation[4]



[4] Sardar, Musaev, and Fetzer, "Demystifying Attestation in Intel Trust Domain Extensions via Formal Verification", 2021

Discrepancies Identified

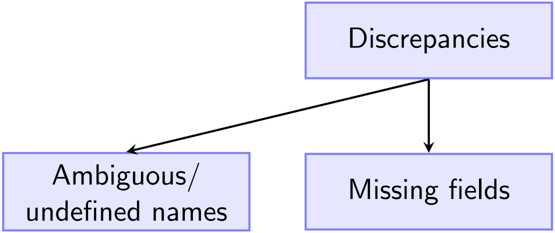


- SEAMINFO vs. TEE_TCB_INFO (e.g., p.2-8)[5]

[5]Intel, *Intel ® Trust Domain CPU Architectural Extensions*, 2020

[6]Intel, *Architecture Specification: Intel® Trust Domain Extensions (Intel® TDX) Module*, 2020

Discrepancies Identified

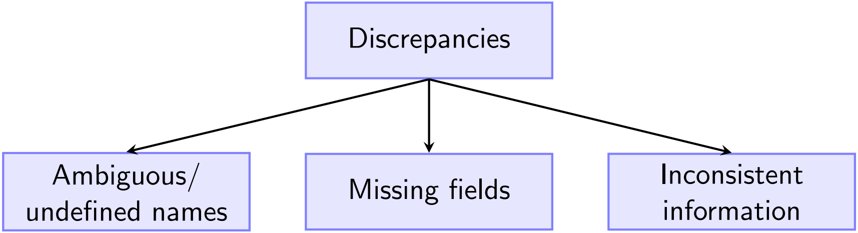


- MROWNERCONFIG missing in TDINFO (Fig. 10.1, p.85)[6]

[5] Intel, *Intel ® Trust Domain CPU Architectural Extensions*, 2020

[6] Intel, *Architecture Specification: Intel® Trust Domain Extensions (Intel® TDX) Module*, 2020

Discrepancies Identified



[5] Intel, *Intel ® Trust Domain CPU Architectural Extensions*, 2020

[6] Intel, *Architecture Specification: Intel® Trust Domain Extensions (Intel® TDX) Module*, 2020

Inconsistent Information: Example 1[7]

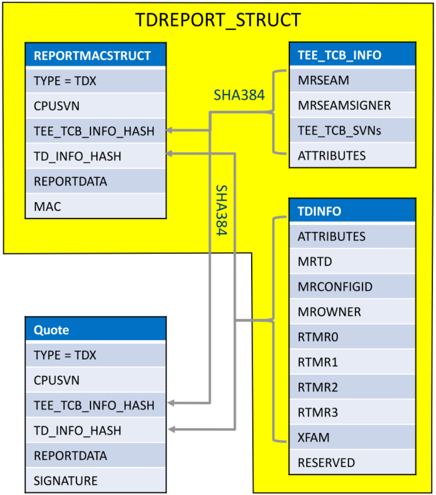


Figure 10.1: TDX Measurement Reporting

[7] Intel, *Architecture Specification: Intel® Trust Domain Extensions (Intel® TDX) Module*, 2020

Inconsistent Information: Example 1[8]

$tmp\_seamreport.REPORTMACSTRUCT.TEE\_TCB\_INFO\_HASH =$
$SHA384(tmp\_seamreport.TEE\_TCB\_INFO);$

Table 2-3. TEE_TCB_INFO Structure

Name	Offset (Bytes)	Size (Bytes)	Description
VALID	0	8	Indicates TEE_TCB_INFO fields which are valid. ▪ 1 in the i-th significant bit reflects that the 8 bytes starting at offset (8 * i) are valid. ▪ 0 in the i-th significant bit reflects that either 8 bytes starting at offset (8 * i) is not populated or reserved, and is set to zero.
TEE_TCB_SVN	8	16	TEE_TCB_SVN array.
MRSEAM	24	48	Measurement of the Intel TDX module.
MRSIGNERSEAM	72	48	Measurement of TDX module signer if valid.
ATTRIBUTES	120	8	Additional configuration ATTRIBUTES if valid.
RESERVED	128	111	Must be zero.

[8] Intel, *Intel ® Trust Domain CPU Architectural Extensions*, 2020

Automated Verification

- Validation: reachability of all parts of code
- Confidentiality: reachability property
- Authentication properties, e.g.,
  $x \equiv \langle rtyp, res1, csvn, tcbh, tdih, rdata, res2 \rangle$

$$\forall\ x.$$
$$\exists\ mac, tcbi.$$
$$event(QuoteVerified(x)) \Rightarrow event(CPUsentSMR(x, mac, tcbi))$$

Outline

Take-home

- TDX specifications are inconsistent and poorly documented

Take-home

- TDX specifications are inconsistent and poorly documented
  - may lead to design and implementation flaws

Take-home

- TDX specifications are inconsistent and poorly documented
  - may lead to design and implementation flaws
- Reported to Intel and being updated by Intel

Take-home

- TDX specifications are inconsistent and poorly documented
  - may lead to design and implementation flaws
- Reported to Intel and being updated by Intel
- Works in progress

Take-home

- TDX specifications are inconsistent and poorly documented
  - may lead to design and implementation flaws
- Reported to Intel and being updated by Intel
- Works in progress
  - Model: PCE and cert chain, verifier end

Take-home

- TDX specifications are inconsistent and poorly documented
  - may lead to design and implementation flaws
- Reported to Intel and being updated by Intel
- Works in progress
  - Model: PCE and cert chain, verifier end
  - Properties:

Take-home

- TDX specifications are inconsistent and poorly documented
  - may lead to design and implementation flaws
- Reported to Intel and being updated by Intel
- Works in progress
  - Model: PCE and cert chain, verifier end
  - Properties:
    - Mutual authentication

Take-home

- TDX specifications are inconsistent and poorly documented
  - may lead to design and implementation flaws
- Reported to Intel and being updated by Intel
- Works in progress
  - Model: PCE and cert chain, verifier end
  - Properties:
    - Mutual authentication
    - Freshness

Take-home

- TDX specifications are inconsistent and poorly documented
  - may lead to design and implementation flaws
- Reported to Intel and being updated by Intel
- Works in progress
  - Model: PCE and cert chain, verifier end
  - Properties:
    - Mutual authentication
    - Freshness
  - Reveal the hidden assumptions of Intel (e.g., on verifier side)

Take-home

- TDX specifications are inconsistent and poorly documented
  - may lead to design and implementation flaws
- Reported to Intel and being updated by Intel
- Works in progress
  - Model: PCE and cert chain, verifier end
  - Properties:
    - Mutual authentication
    - Freshness
  - Reveal the hidden assumptions of Intel (e.g., on verifier side)
- Shameless plug: we are hiring PhDs, post-docs ([muhammad_usama.sardar,christof.fetzer]@tu-dresden.de)

Key References I

- Blanchet, Bruno et al. "Modeling and verifying security protocols with the applied pi calculus and ProVerif". In: *Foundations and Trends in Privacy and Security* 1.1-2 (2016), pp. 1–135.
- Confidential Computing Consortium. *Whitepaper feedback from Muhammad Usama Sardar, Issue #77*. 2020. URL: https://github.com/confidential-computing/governance/issues/77 (visited on 09/13/2021).
- Intel. *Architecture Specification: Intel® Trust Domain Extensions (Intel® TDX) Module*. Sept. 2020. URL: https://software.intel.com/content/dam/develop/external/us/en/documents/intel-tdx-module-1eas.pdf.
- — .*Intel ® Trust Domain CPU Architectural Extensions*. Sept. 2020. URL: https://software.intel.com/content/dam/develop/external/us/en/documents/intel-tdx-cpu-architectural-specification.pdf.
- Sardar, Muhammad Usama and Christof Fetzer. *Confidential Computing and Related Technologies : A Review*. 2021. URL: https://www.researchgate.net/publication/356474602_Confidential_Computing_and_Related_Technologies_A_Review.
- Sardar, Muhammad Usama, Saidgani Musaev, and Christof Fetzer. "Demystifying Attestation in Intel Trust Domain Extensions via Formal Verification". In: *IEEE Access* (2021). URL: https://www.researchgate.net/publication/351699567_Demystifying_Attestation_in_Intel_Trust_Domain_Extensions_via_Formal_Verification.