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BIinded Memory

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(Joint work with Hossam ElAtali, Lachlan J. Gunn, John Z. Jekel, Hans Liljestrand)

This talk in a nutshell

1. Outsourced computing is everywhere…

- Machine learning models kept behind remote APIs

2. …but this introduces security risks…

- Providers don't expose models/code to clients
- Clients expose sensitive data to providers
- Existing solutions like FHE/TEEs have drawbacks

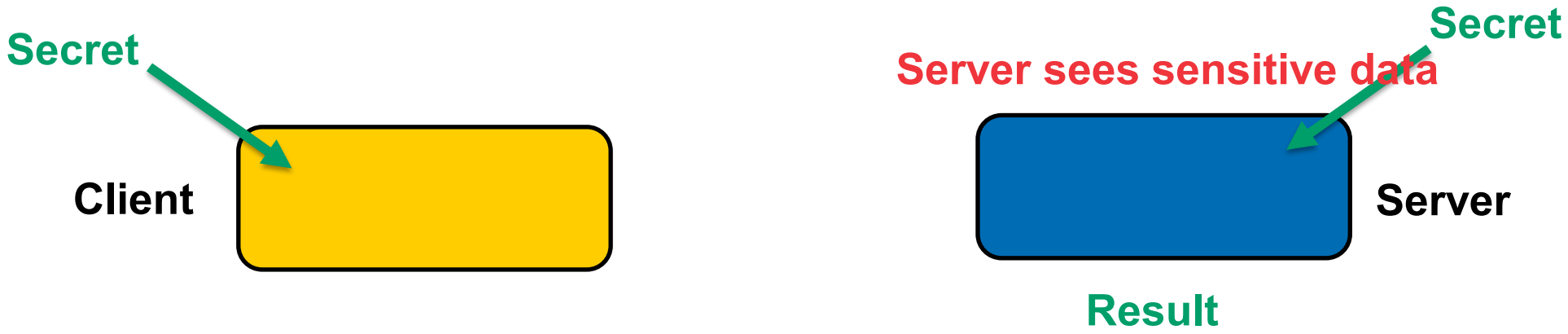
3. …so we propose a new solution, Blinded Memory

- Attestation + standard encryption + hardware-assisted taint tracking
- Sensitive data not exposed to output devices or covert channels

Scenario: outsourced computation

Goal: run the server's confidential code over client's confidential data

- Initial target: Outsourced ML inference and/or training

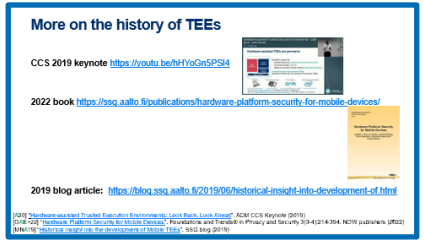


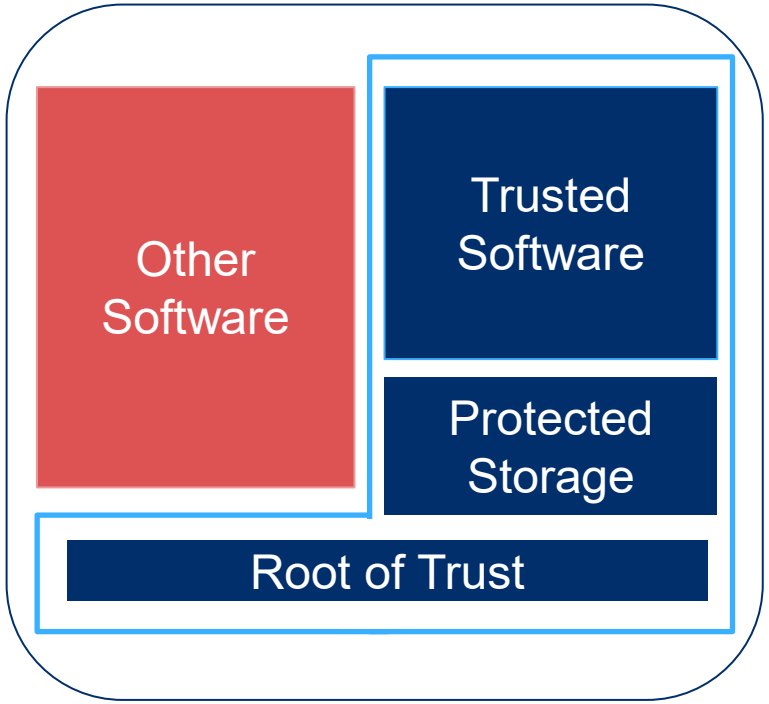
How can the client avoid revealing data to the service provider?

- Fully-Homomorphic Encryption: slow due to computational overhead
- Multi-Party Computation: slow due to network overhead

- **Hardware-based isolation + remote attestation: fast**

Hardware-assisted TEEs are pervasive





Hardware support for

- **Isolated execution: Isolated Execution Environment**
- **Protected storage: Sealing**
- **Ability to convince remote verifiers: (Remote) Attestation**

Trusted Execution Environments (TEEs)
Operating in parallel with "rich execution environments" (REEs)

Cryptocards

https://www.ibm.com/security/cryptocards/

Trusted Platform Modules

https://www.infineon.com/tpm

ARM TrustZone

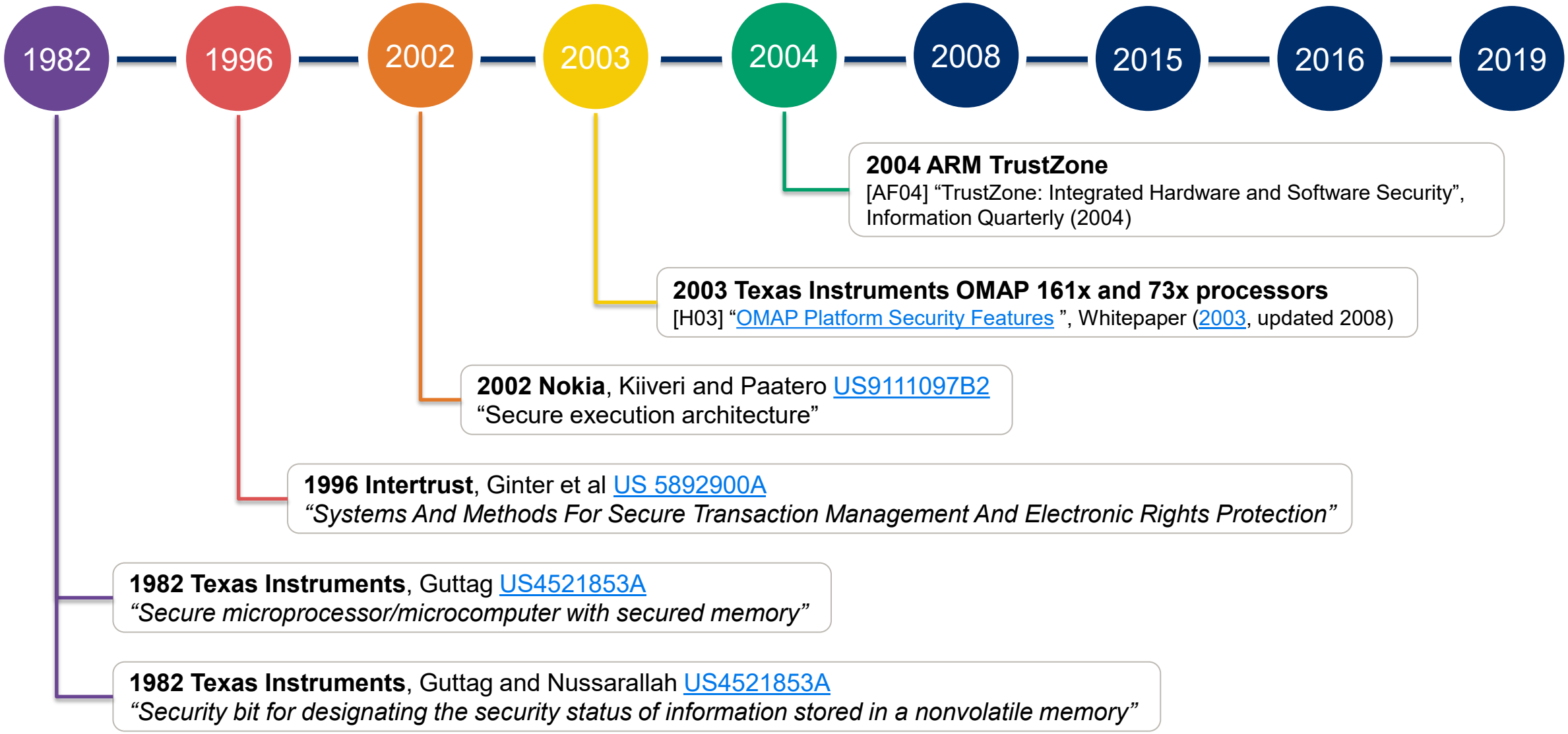
https://www.arm.com/products/security-on-arm/trustzone

Intel Software Guard Extensions

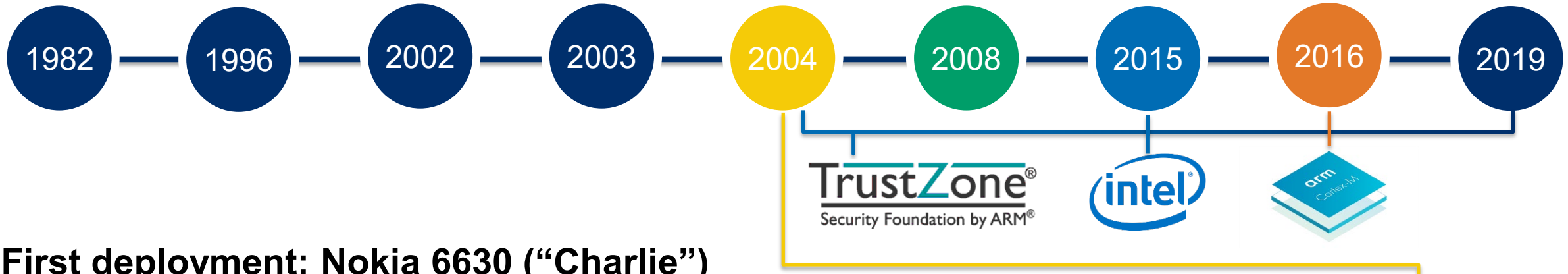
https://software.intel.com/en-us/sgx

[A+14] "Mobile Trusted Computing", Proceedings of the IEEE, 102(8) (2014)
[EKA14] "Untapped potential of trusted execution environments", IEEE S&P Magazine, 12:04 (2014)

TEEs as an idea date back to the 1980s



Deployment of mobile TEEs date back to the 2000s



First deployment: Nokia 6630 (“Charlie”)

- first 3G phone with TI OMAP 1710 processor (June 2004)

ARM TrustZone currently widely deployed

- TrustZone-M for Cortex-M class microcontrollers (2016)

Ca. 2008, TEE unheard of in academic circles

- first papers in FC 2008, ASIACCS 2009

  [AE08] A Platform for OnBoard Credentials, Financial Cryptography and Data Security (2008)
  [KEAR09] On-board credentials with open provisioning, ACM ASIACCS (2009)

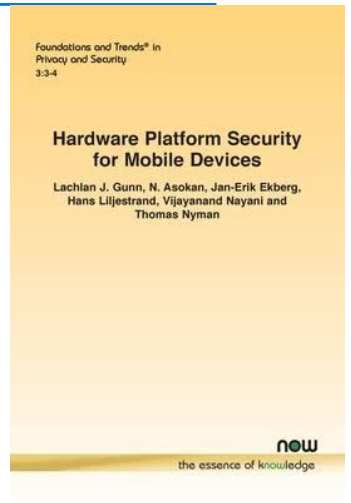
Intel SGX

- SkyLake (2015); wide availability of SDK “democratized” TEE research

More on the history of TEEs

CCS 2019 keynote https://youtu.be/hHYoGn5PSI4

2022 book https://ssg.aalto.fi/publications/hardware-platform-security-for-mobile-devices/



2019 blog article: https://blog.ssg.aalto.fi/2019/06/historical-insight-into-development-of.html

[A20] "Hardware-assisted Trusted Execution Environments: Look Back, Look Ahead", ACM CCS Keynote (2019)
[GAE+22] "Hardware Platform Security for Mobile Devices", Foundations and Trends® in Privacy and Security 3(3-4):214-394, NOW publishers (2022)
[MNA19] "Historical insight into the development of Mobile TEEs", SSG blog (2019)

Protection provided by TEEs comes with caveats

TEEs provide an isolated environment for execution of software

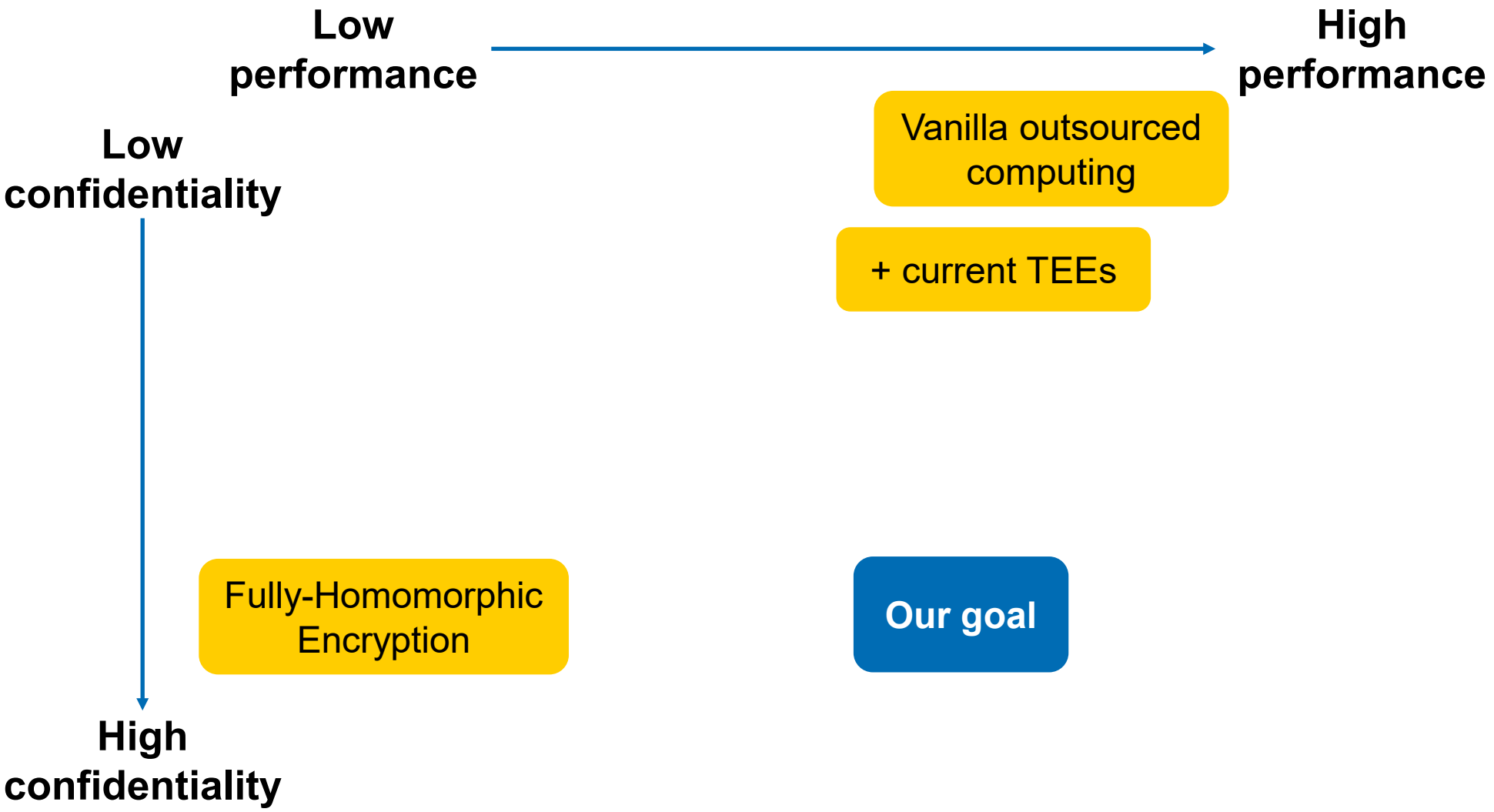
TEEs are unsuitable when server code is confidential or unverfiable

- TEEs intended for clients to run code they trust and can verify

Confidentiality of client data in TEEs is hampered by:

- **Large TEE code base → vulnerable to software flaws**
- **Sharing resources → vulnerable to side channels**

Is Confidentiality vs. Performance a tradeoff?



What can be done?

1. **Prevent application software from leaking sensitive data**
   - Use hardware-assisted taint-tracking
   - Need not verify trustworthiness of application s/w

2. **Minimize resource sharing**
   - Move critical operations to a fixed-function, isolated processor (HSM)
   - All HSM code analyzed in advance, guaranteed not to be malicious

Prevent leakage of sensitive data via CPU extensions

“Safe” streams of instructions don’t expose sensitive data

Allowed:

- Computation on sensitive data by arbitrary, unattested, untrusted software

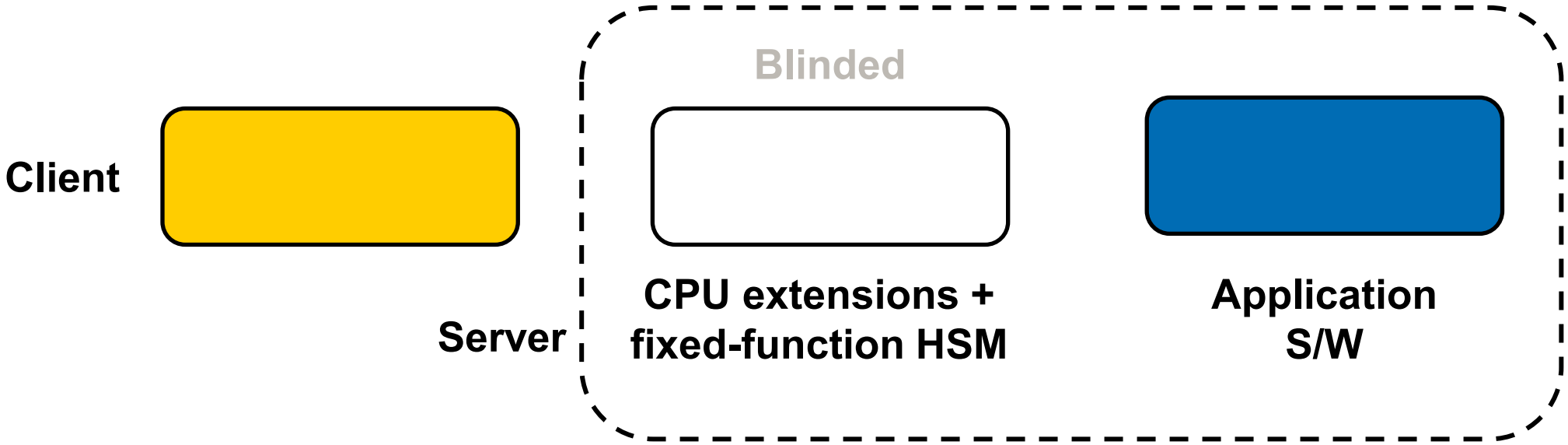
Prohibited:

- Leaking sensitive data into any observable state, e.g.: peripherals outside security boundary, microarchitectural state

Use taint-tracking-based security policy to limit sensitive data to safe places

Combine with attestable HSM to assure clients

Remote attestation assures use of client data is subject to security policy



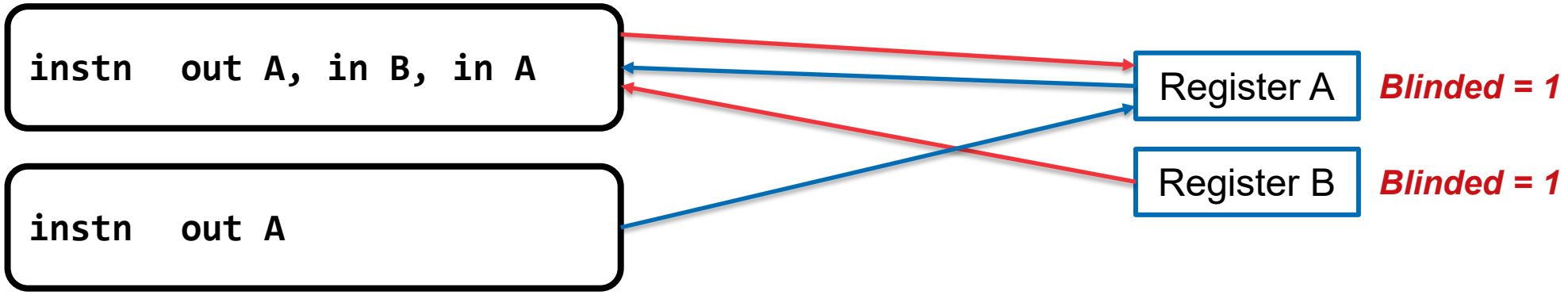
Taint tracking policy

Registers/memory have an associated "sensitive" bit ("Blinded")

Ideal rule:

$\text{Blinded}(\text{output}_m) \leftarrow \exists n,m: \text{Blinded}(\text{input}_n) \wedge \text{Depends}(\text{output}_m \text{ on } \text{input}_n)$

Goal: changes in sensitive state never affect non-sensitive state



Thinking beyond registers and memory

Taint-propagation rule must consider many different observable outputs

- Registers
- Memory values
- Control flow

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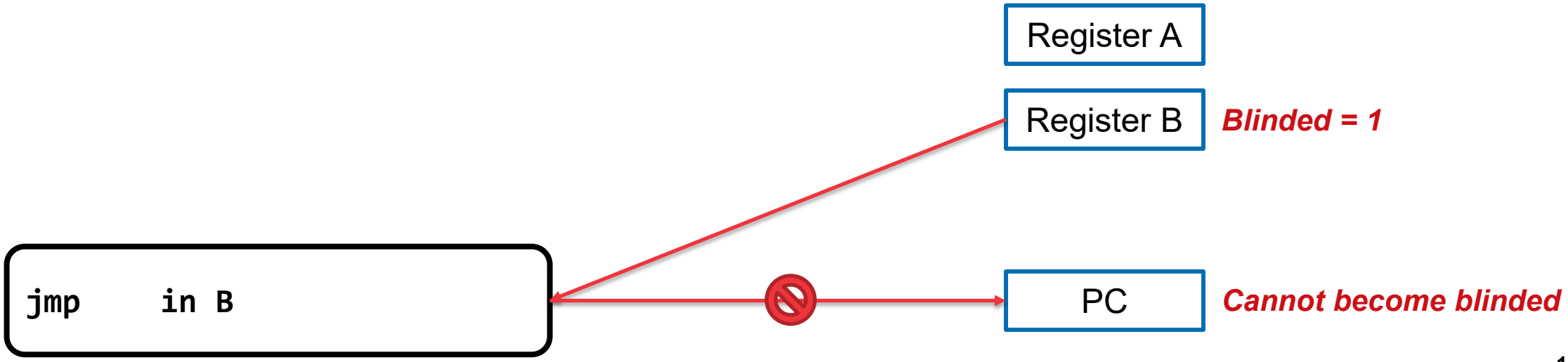


Thinking beyond registers and memory

Taint-propagation rule must consider many different observable outputs

- Registers
- Memory values
- Control flow
- Exceptions
- Memory access patterns

Not all of these outputs can be marked as sensitive

Data flows from sensitive values to "un-markable" outputs must yield a fault

How to deal with exceptions

Examples of data-dependent exceptions:

- Division by zero
- Floating-point exceptions
- …

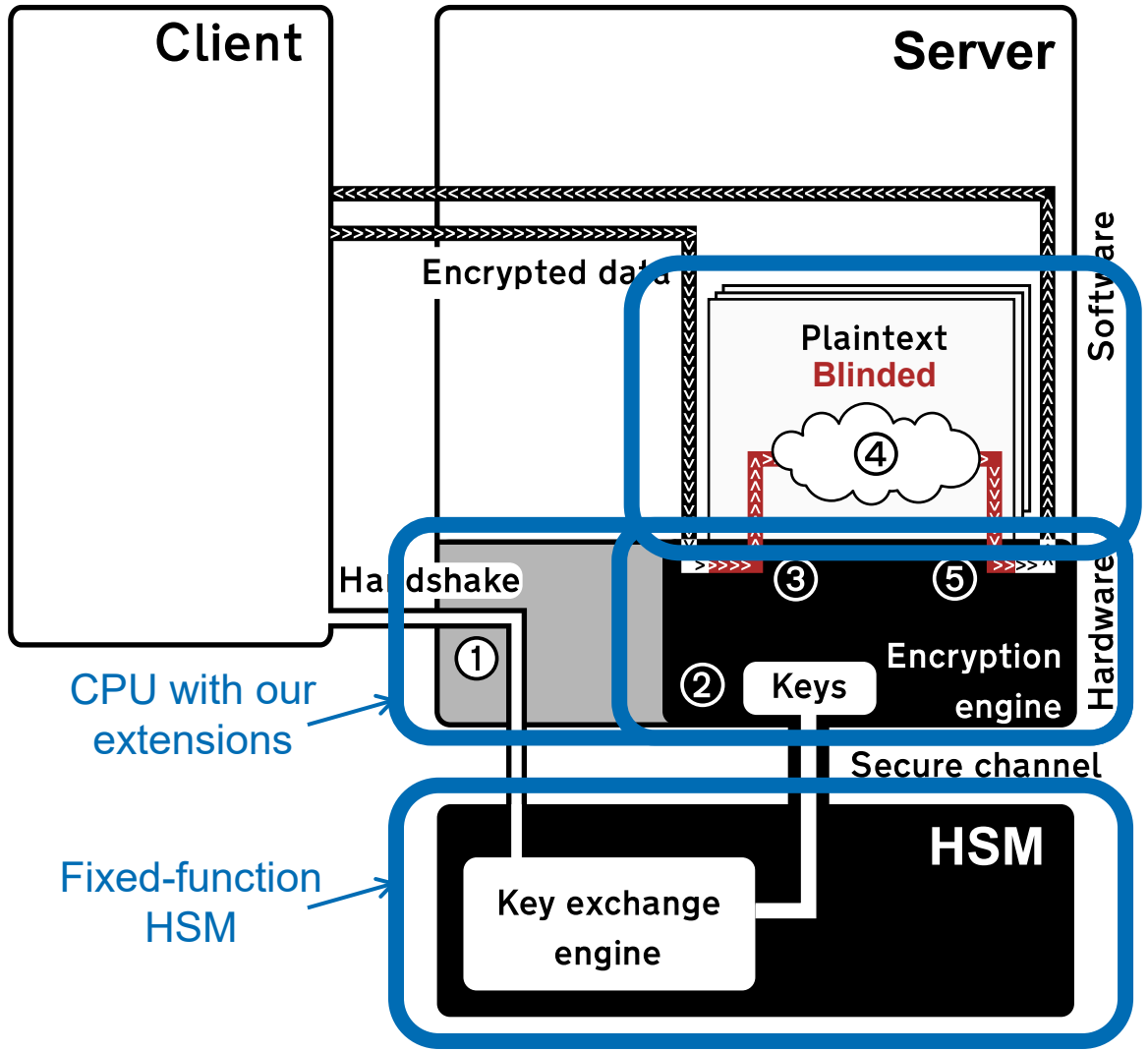
Instructions must not raise an exception based on data-dependent conditions

Solutions:

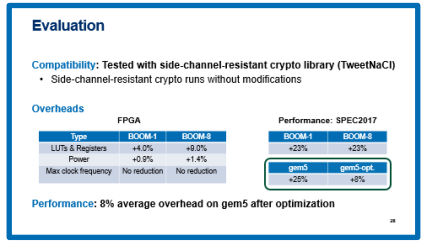
- Unconditional faults (i.e., division by sensitive values always fails)
- Set a sensitive error flag and continue computation

BliMe Architecture

1. **Handshake (incl. remote attestation)**
2. **Shared secret key**
3. **Atomic data import (inputs)**
   - Decrypt & blind (Blinded ← true)
4. **Safe (“blinded”) computation**
   - Enforced by BliMe HW extensions
5. **Atomic data export (result)**
   - Encrypt & unblind (Blinded ← false)



BliMe-BOOM Implementation

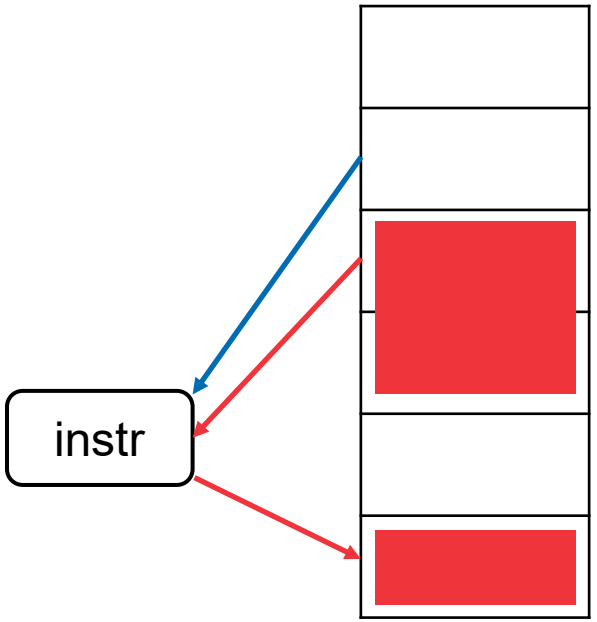


On speculative OoO RISC-V core BOOM

Tagged memory: each byte can be marked as blinded

Instructions to mark physical memory as

- Blinded or non-Blinded



Implements taint-tracking for all instructions

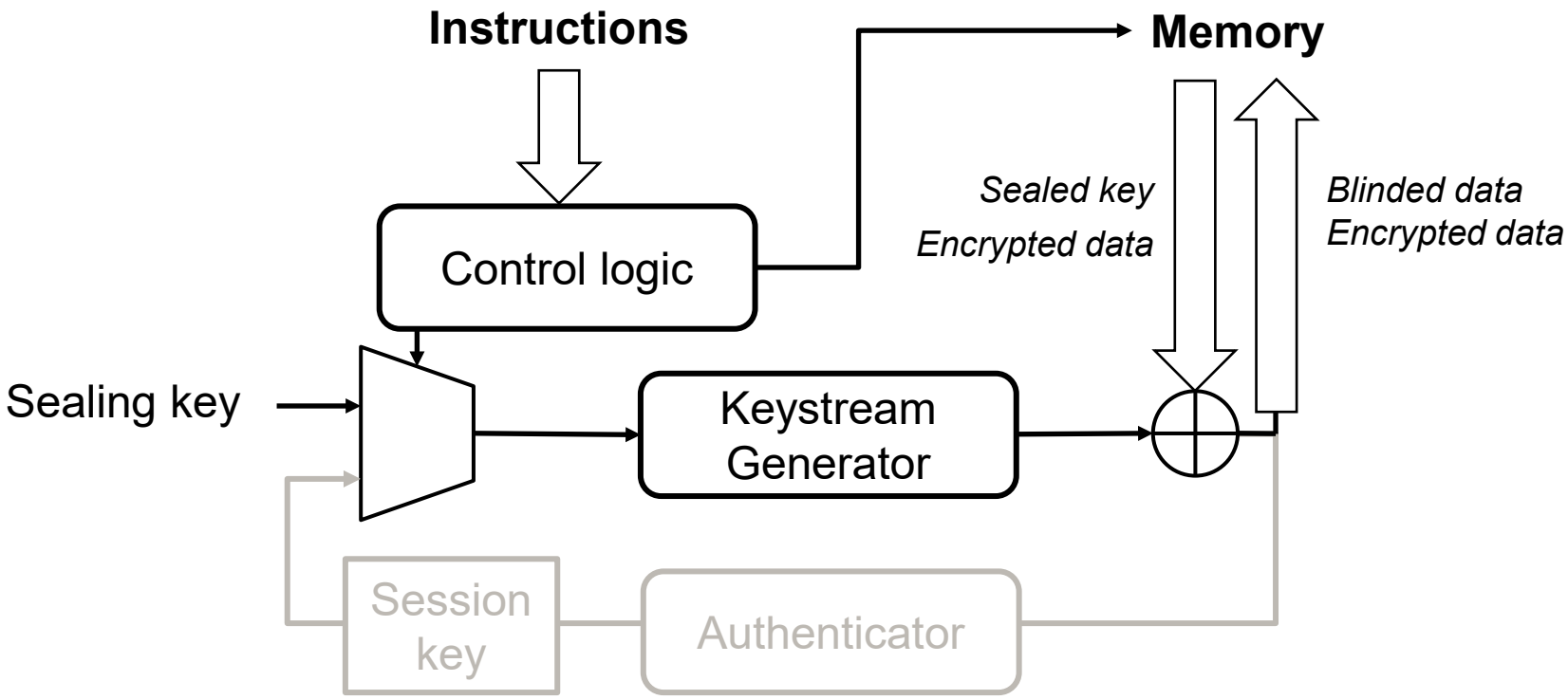
- Ideal rule: $\text{Blinded}(\text{output}_m) \leftarrow \exists n,m: \text{Blinded}(\text{input}_n) \wedge \text{Depends}(\text{output}_m \text{ on } \text{input}_n)$
  Approx. to: $\text{Blinded}(\text{outputs}) \leftarrow \text{Blinded}(\text{input}_1) \vee \text{Blinded}(\text{input}_2) \vee \ldots$

Approximation can be overridden for specific instructions

Encryption Engine

Encryption engine uses the RoCC accelerator interface in BOOM

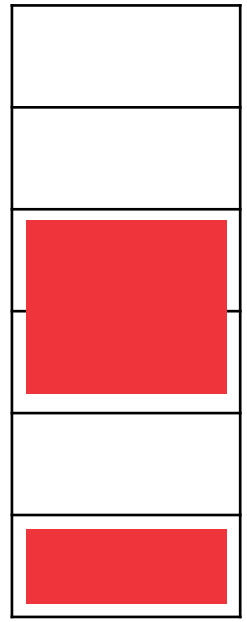
- RoCC exposes custom logic as instructions



Handling multiple clients simultaneously

Problem: So far, one Blinded bit for many clients

- Server can send sensitive data to the wrong client



We need a separate sensitivity domain for each client

- Prevent clients accessing each other's sensitive data
- Keys need to be swapped in and out for each client

Handling multiple clients simultaneously

Solution 1: BliMe-BOOM-1 + Isolation by honest-but-curious server OS

- OS keeps track of sensitivity domains
- Requires only single Blinded bit from HW: low memory overhead
- Rely on remote attestation of the entire OS to convince client

Solution 2: BliMe-BOOM-N -- Hardware support for multiple clients

- Hardware keeps track of sensitivity domains: multibit Blindedness tag
- Secure despite malicious OS
- Needs extra memory/logic to keep track of domain identifier for each granule

BliMe-BOOM-N Implementation

BOOM RTL

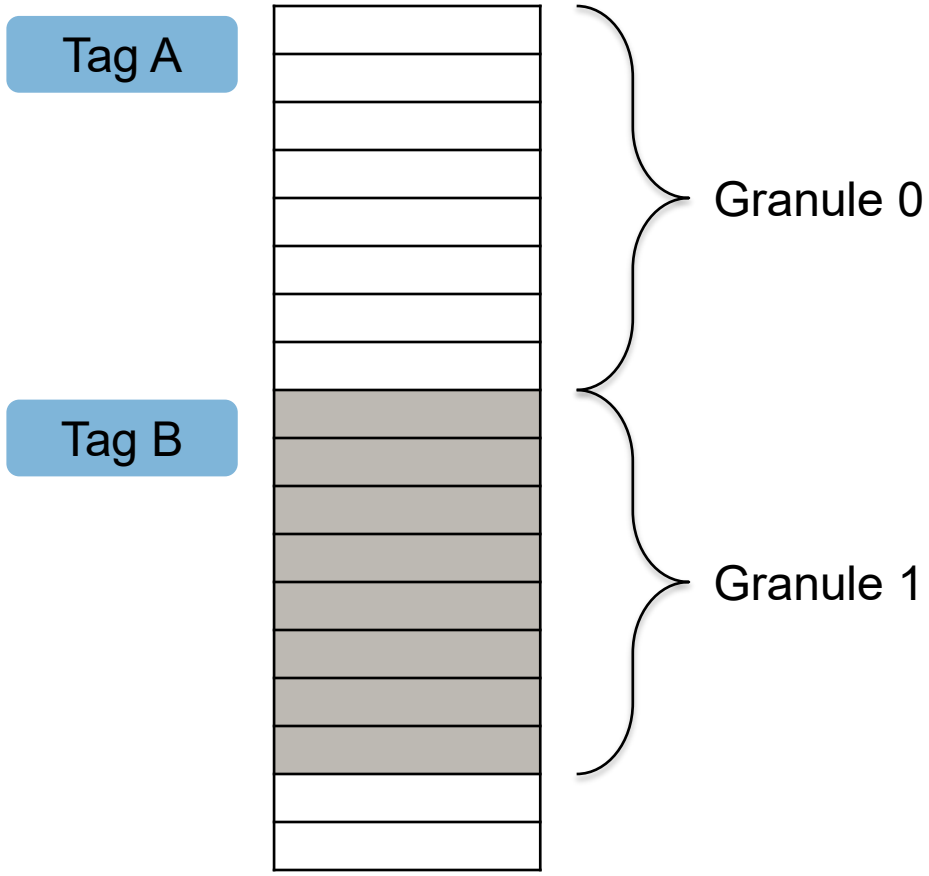
Data tagged with client-specific tag

1 tag per granule

Tag size = 8 bits, granule size = 8 bytes

Future work:

- parameterize tag size and granule size



Evaluation

Compatibility: Tested with side-channel-resistant crypto library (TweetNaCl)

- Side-channel-resistant crypto runs without modifications

Overheads

FPGA

Type	BOOM-1	BOOM-8
LUTs & Registers	+4.0%	+9.0%
Power	+0.9%	+1.4%
Max clock frequency	No reduction	No reduction

Performance: SPEC2017

BOOM-1	BOOM-8
+23%	+23%

BliMe-gem5 optimization

BliMe-BOOM uses same memory request size for data and tags

Using correct request size (1/8th) needs extensive changes to baseline

Solution: Use gem5 simulator to perform evaluation with correct size

- BliMe-gem5-optimized

Could Δ in performance just be caused by moving to gem5?

- Implement BliMe-gem5 with BliMe-BOOM configs
- BliMe-gem5 matches BliMe-BOOM in average performance (SPEC 2017)

Evaluation

Compatibility: Tested with side-channel-resistant crypto library (TweetNaCl)

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Overheads

FPGA

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Performance: SPEC2017

BOOM-1	BOOM-8
+23%	+23%

gem5	gem5-opt.
+25%	+8%

Performance: 8% average overhead on gem5 after optimization

Security: Formal verification in F*

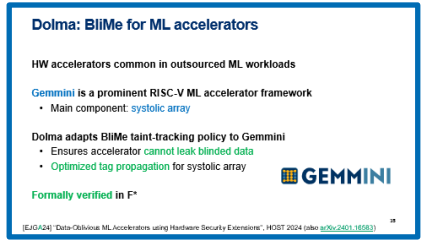
Goal: changes in blinded state never affect non-blinded state

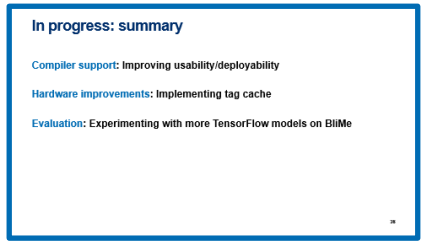
```
(*****************************************************************
 * Equivalence-based safety.
 *
 * We define safety in this case to be that the system is safe if executing on
 * equivalent (and so indistinguishable) states always results in equivalent
 * output states.
 *****************************************************************)
let equivalent_inputs_yield_equivalent_states (exec:execution_unit) (pre1 pre2 : systemState) =
    equiv_system pre1 pre2 ⇒ equiv_system (step exec pre1) (step exec pre2)


let is_safe (exec:execution_unit) =
    ∀ (pre1 pre2 : systemState). equivalent_inputs_yield_equivalent_states exec pre1 pre2
```

https://blinded-computation.github.io/blime-model/

Generating compliant code with LLVM





Problem: software might not run as-is

- BliMe hardware extensions will abort non-compliant code

Creating compliant code by hand is error prone

- High-level verification often insufficient
- Challenge exacerbated due to obtuse compiler behavior
- Usability/deployability challenge, not security

TensorFlow Lite hand-ported to run on BliMe

Challenge: solutions like Constantine[B+21] are not applicable as-is

- Uses dynamic profiling; under-approximates taint (best-effort approach)

[B+21] "Constantine: Automatic Side-Channel Resistance Using Efficient Control and Data Flow Linearization", ACM CCS (2021)

Generating compliant code with LLVM: our solution

Solution: Use static analysis to propagate taint

- Trade-off: over-approximation

Use SVF[S+16] as a starting point

SVF provides static value-flow graph

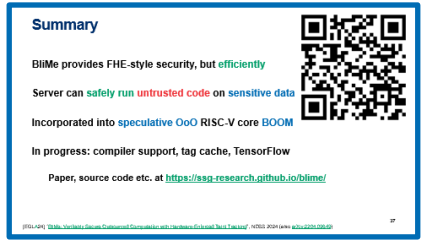
- Shows value dependencies within program

Identify and transform potential violations

- Apply data- and control-flow linearization

[S+16] "SVF: interprocedural static value-flow analysis in LLVM", ACM International Conference on Compiler Construction (2016)

Adapting TensorFlow Lite to BliMe



Compiled image classification example

Some manual fixes required in TensorFlow Lite library source code

- e.g., array access expansion for softmax lookup table

In progress:

- For TensorFlow Lite: try more example models
- For the compiler
  - Ensure soundness
  - Produce warnings for untransformed libraries

Dolma: BliMe for ML accelerators

HW accelerators common in outsourced ML workloads

Gemmini is a prominent RISC-V ML accelerator framework

- Main component: systolic array

Dolma adapts BliMe taint-tracking policy to Gemmini

- Ensures accelerator cannot leak blinded data
- Optimized tag propagation for systolic array

Formally verified in F*

[EJGA24] “Data-Oblivious ML Accelerators using Hardware Security Extensions”, HOST 2024 (also arXiv:2401.16583)

In progress: summary

Compiler support: Improving usability/deployability

Hardware improvements: Implementing tag cache

Evaluation: Experimenting with more TensorFlow models on BliMe

Summary

BliMe provides FHE-style security, but efficiently

Server can safely run untrusted code on sensitive data

Incorporated into speculative OoO RISC-V core BOOM

In progress: compiler support, tag cache, TensorFlow

Paper, source code etc. at https://ssg-research.github.io/blime/

[EGLA24] "BliMe: Verifiably Secure Outsourced Computation with Hardware-Enforced Taint Tracking", NDSS 2024 (also arXiv:2204.09649)

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If this type of work interests you, come work with us!
https://asokan.org/asokan/research/SecureSystems-open-positions-Jan2024.php

[EGLA24] "BliMe: Verifiably Secure Outsourced Computation with Hardware-Enforced Taint Tracking", NDSS 2024 (also arXiv:2204.09649)