# Applying Runtime Verification to Group Key Establishment

Secure Communication in the Quantum Era
(SPS G5448)

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NATO
OTAN

# The Project

Collaboration between Slovakia, Malta, US, and Spain:

**Secure Communication in the Quantum Era**

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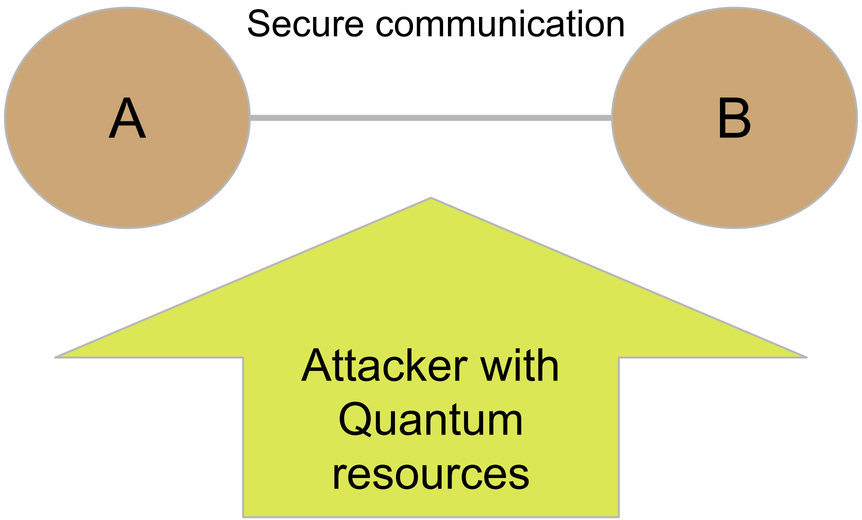

# Authenticated group key establishment (AGKE)

Secure communication depends on establishing **common secret key**

**Project will focus on securing AGKE**

# Authenticated group key establishment (AGKE)

**First step: Designing a protocol**

a) $A$ sends $B$ the message $(A, E_B(MA), B)$,
b) $B$ answers $A$ by sending $(B, E_A(MB), A)$.

# Authenticated group key establishment (AGKE)

First step: Designing a protocol

**Second step: Proving it is correct in principle**

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# Authenticated group key establishment (AGKE)

First step: Designing a protocol

Second step: Proving it is correct in principle

**Third step: What can go wrong at runtime?**

a) $A$ sends $B$ the message $(A, E_B(MA), B)$,
b) $B$ answers $A$ by sending $(B, E_A(MB), A)$.

# What can go wrong at runtime?

| | |
|---|---|
| **(High level) Wrong protocol implementation** | The protocol implementation might deviate from the verified (theoretical) design |
| **Low level threats** | Arithmetic overflows, undefined downcasts, and invalid pointer references |
| **Hardware** | Can hardware be trusted? |

# Passive / Active attacks

Something bad accidentally happens

Vs

Something bad actively sought

# What can go wrong at runtime?

...but in practice is far from enough

**(High level) Wrong protocol implementation**

The protocol implementation might deviate from the verified (theoretical) design

Medium level threats: Malware, Data leaks, etc

**Low level threats**

and invalid pointer references

**Hardware**

Can hardware be trusted?

# Unintended consequences

- Timing attacks
- Cache timing attacks
- Microarchitecture side-channel attack
- Power/EM/acoustic attacks
- Fault attacks
- Reaction attacks
- Data remanence attacks
- Attacks on random number generators

# Timing attack

If (secret)

    Do something lengthy

Else

    Do something simple

An external observer can learn the secret by observing the duration of the execution.

(or the power used or any other side effect)

# What can we do?

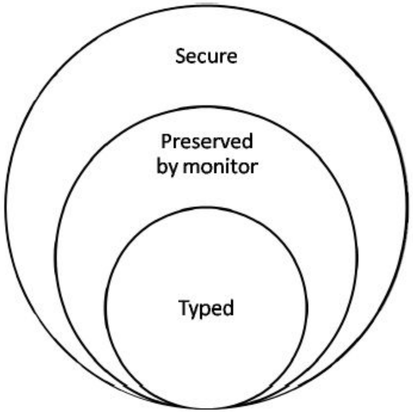
Static + Dynamic analysis of the code to make sure secrets can’t be leaked

# Dynamic analysis

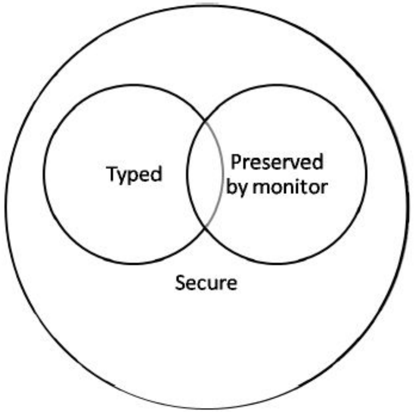
$$\texttt{if } h = 1 \texttt{ then } b := 1 \texttt{ else skip;}$$
$$\texttt{if } b \neq 1 \texttt{ then } l := 1 \texttt{ else skip;}$$
$$\texttt{output}_L(l)$$

Assume h is a high security variable
When h != 1,
Monitor can’t mark b as high
(without analysing the “if” statically)

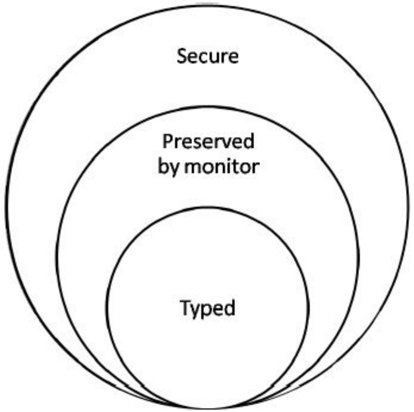
# Soundness/Completeness of dynamic analysis



(a) Flow-insensitive analysis

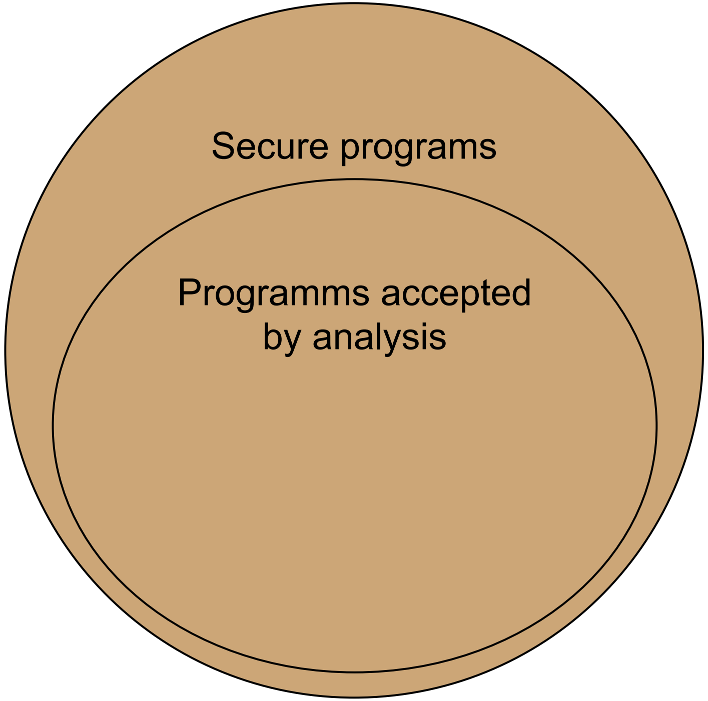


(b) Flow-sensitive analysis

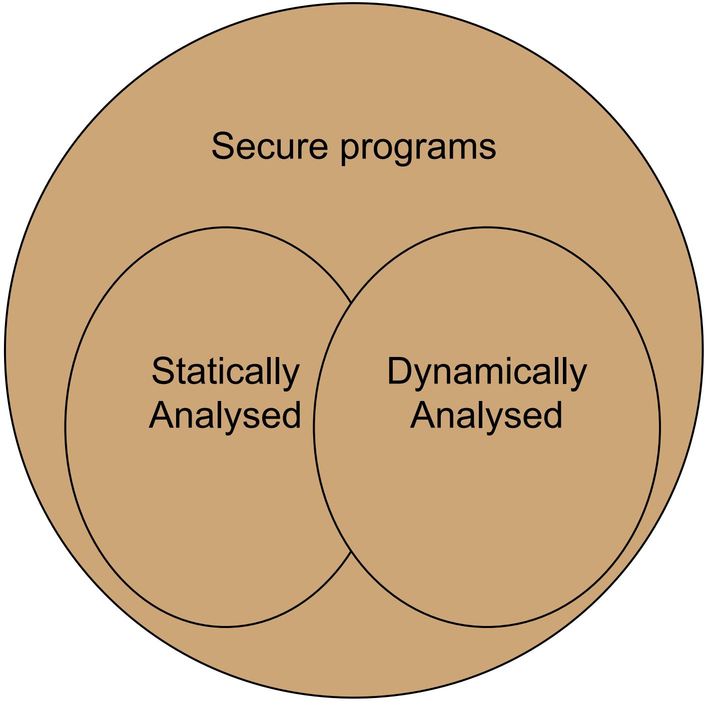


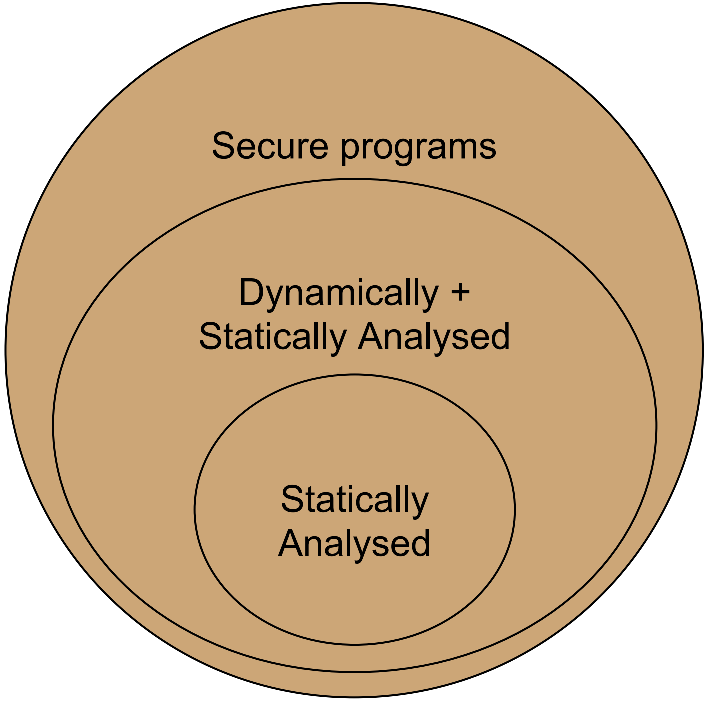
(c) Flow-sensitive analysis, *hybrid* monitors

# Identifying secure programs



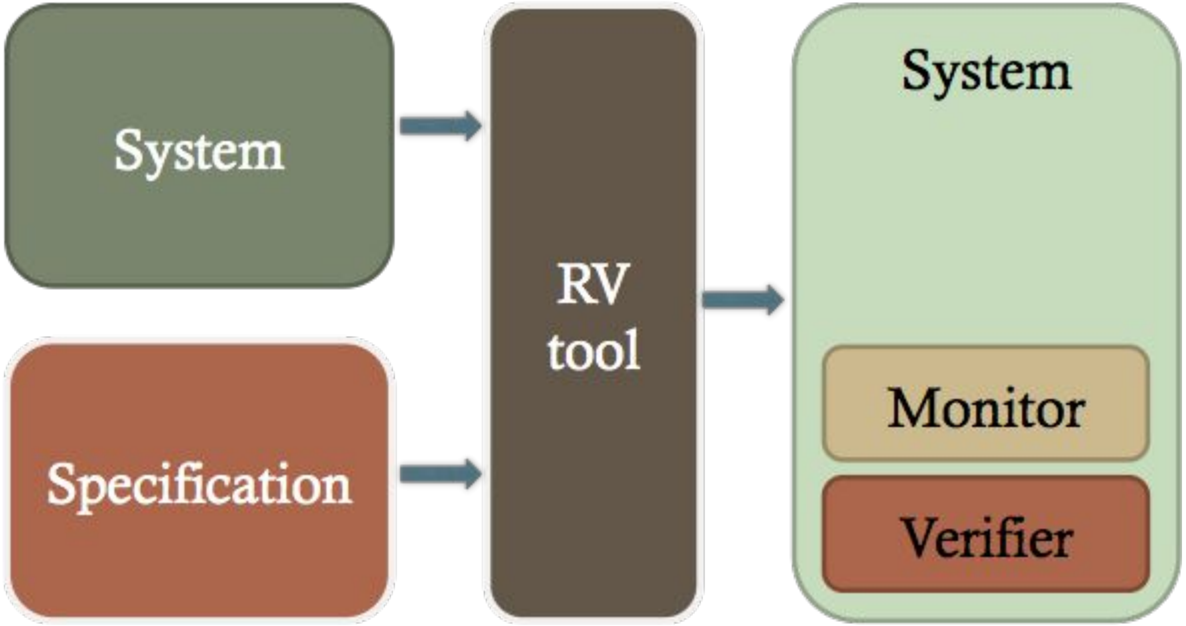
# Soundness/Completeness of dynamic analysis



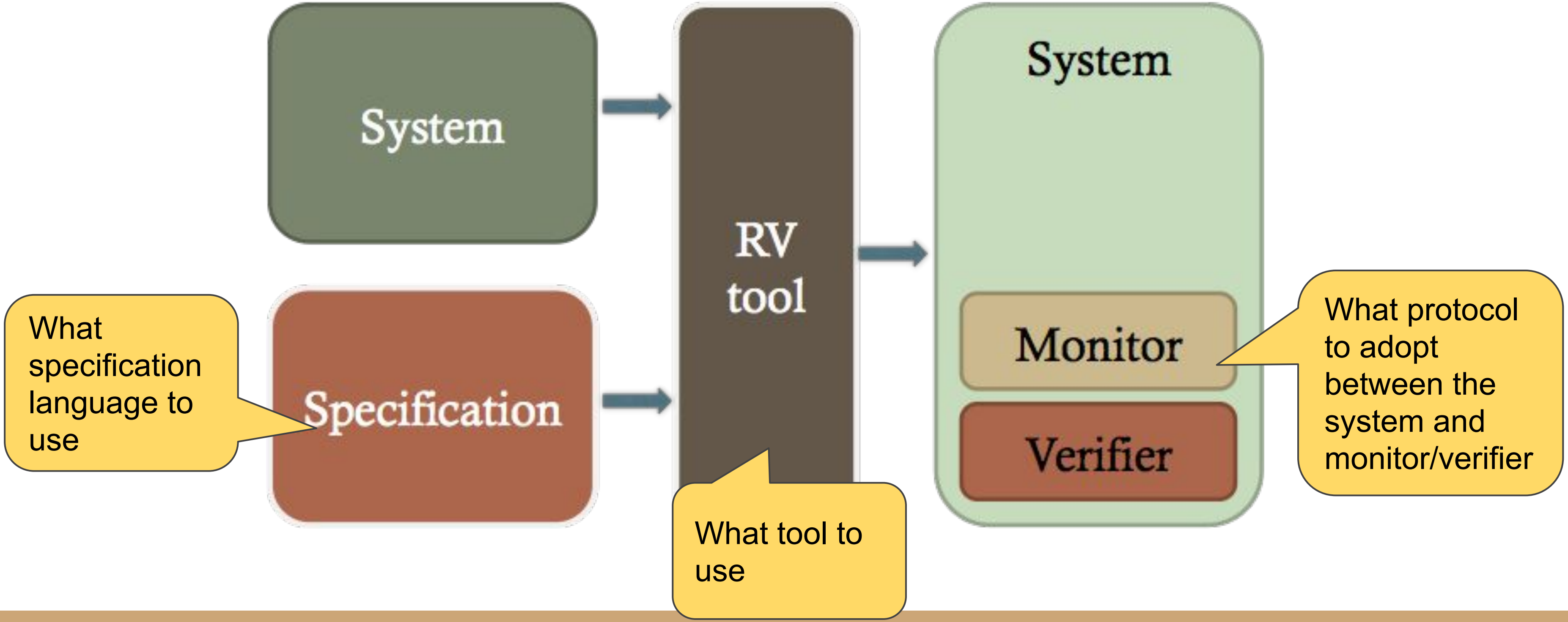



# How do we use these techniques in practice?

# Runtime Verification



# Runtime Verification



# What has been done?

# High level logic

- Before any data is sent by the client,

  the server hash is verified to match the client's version

- If the operation is of type “Send”,

  then the message receiver ID must be in the set of approved receiver IDs

# Low level considerations

General considerations for any code

- Arithmetic overflows
- Undefined downcasts
- Invalid pointer references

# Mid-level

Applicable to any crypto protocol

Data flow monitoring

**E.g. Ensuring no control is decided on secret data**

(which affects the timing of the program)

# Frama-C

Is a framework supporting all of these levels
*(combining static and dynamic checking)*

Low-level is inbuilt through standard checks

Mid-level is provided through library support

High-level is provided through specification languages

# Other tools/frameworks?

Copilot and other tools focus more on high level properties

Work on hyperproperties

- I.e. properties on several runs of a program

# What are the challenges?

# Challenges for RV

Over and above the usual correctness and **overheads** concerns

The monitor can present an additional security vulnerability

>> As a piece of code

>> As a reaction-triggering device

# Other techniques?

For example Multi-execution approach:

Generate low security outputs with only low security inputs in the system

→ **Result:** No high security output may depend on low security input

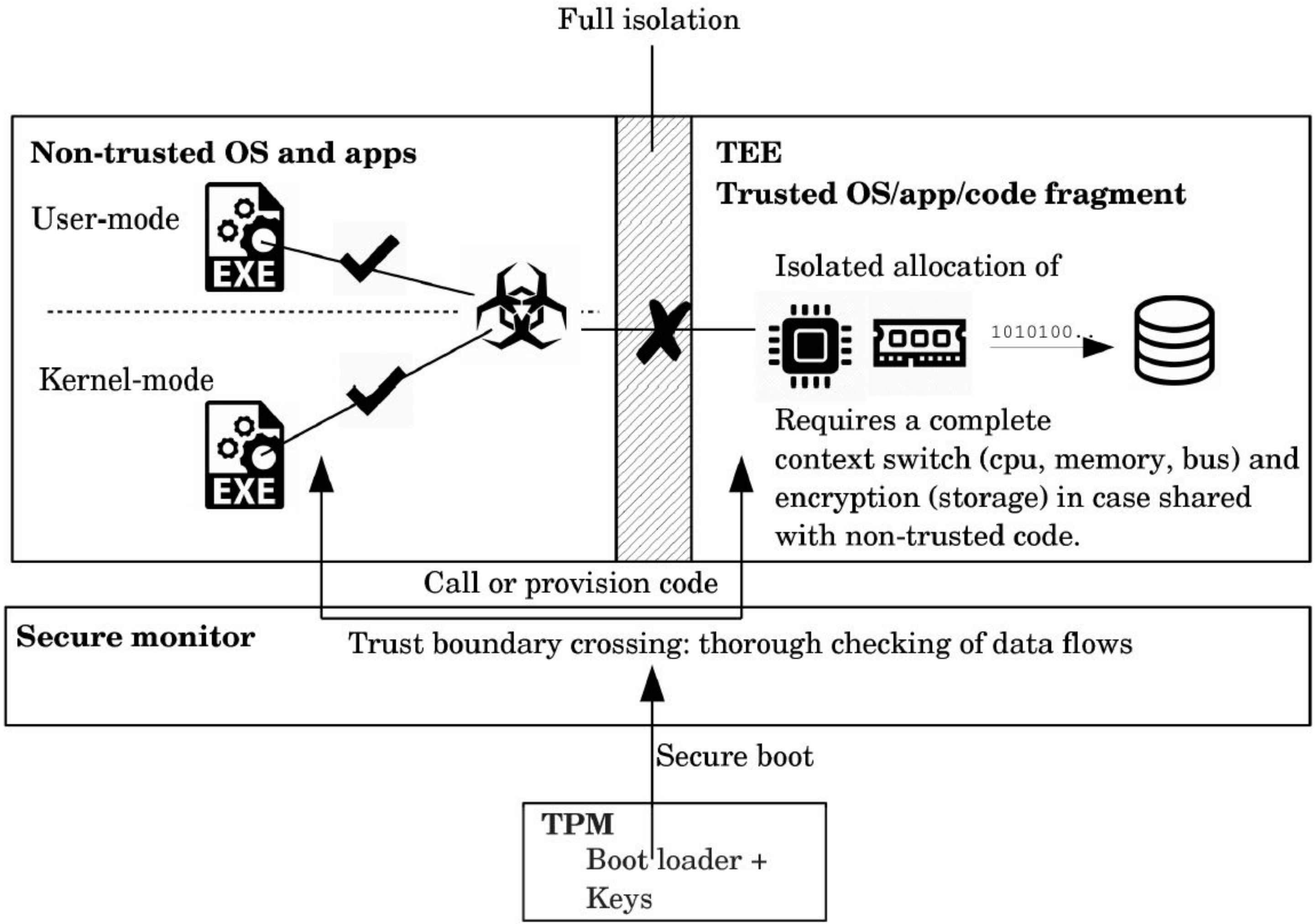
# Our plan of comprehensive approach: Trusted Execution Environment (TEE)

# Questions to be answered

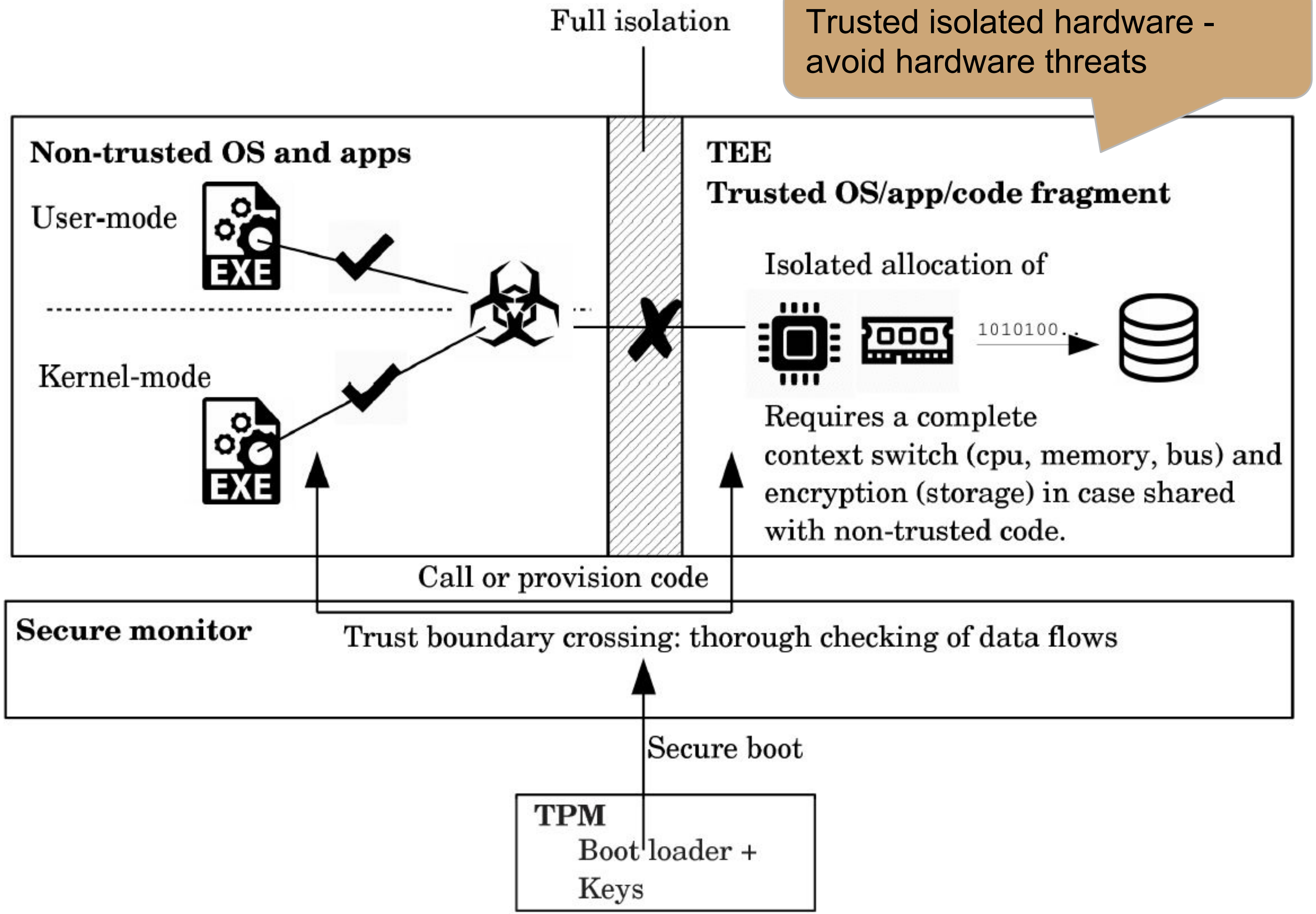
To what extent existing tools/frameworks are immune to attacks themselves

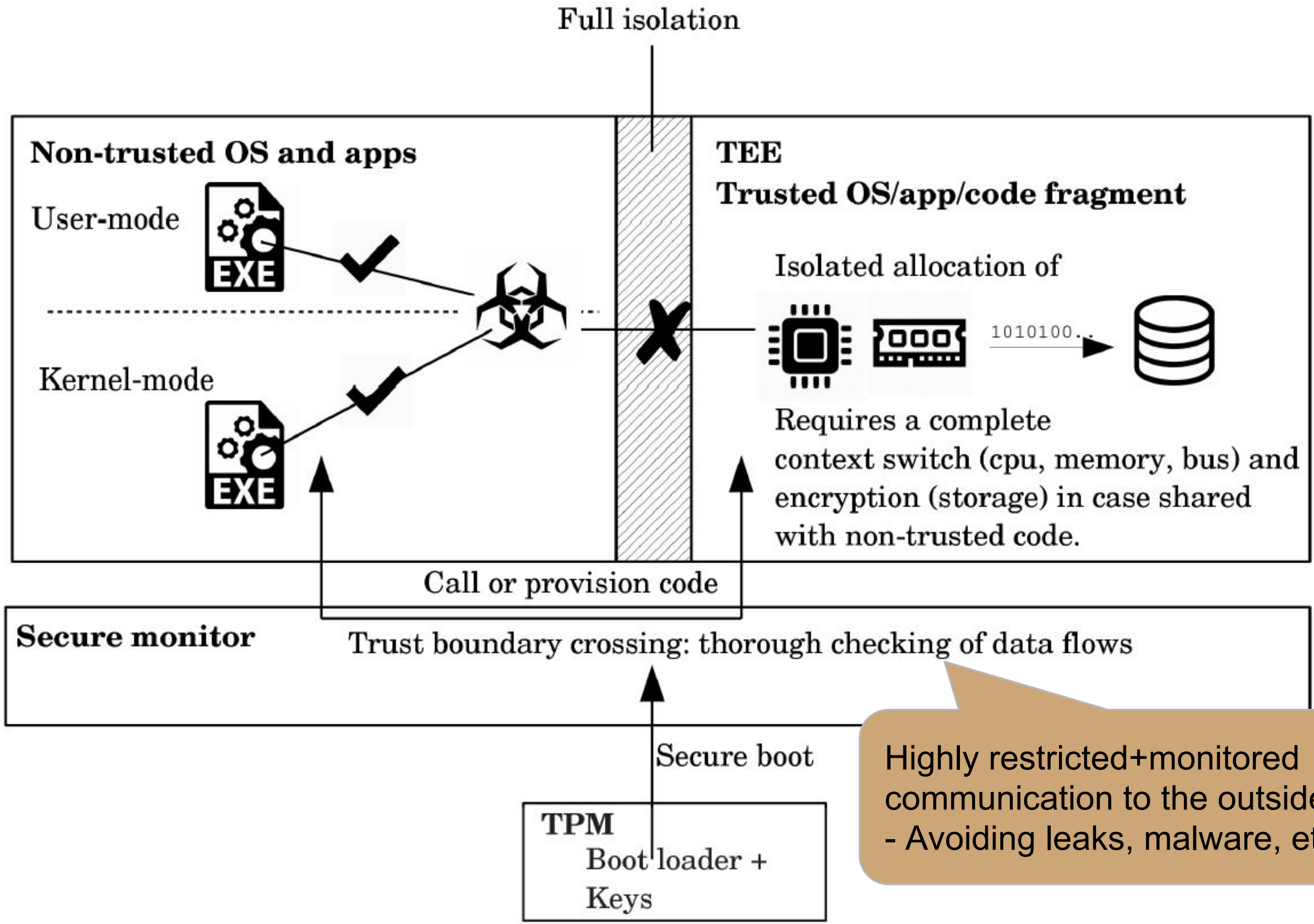
Is there any effect of the quantum prospect on RV?

What mix of new/existing techniques + technologies to adopt


Full isolation
Non-trusted OS and apps
User-mode
EXE
Kernel-mode
EXE
TEE
Trusted OS/app/code fragment
Isolated allocation of
1010100...
Requires a complete
context switch (cpu, memory, bus) and
encryption (storage) in case shared
with non-trusted code.
Call or provision code
Secure monitor
Trust boundary crossing: thorough checking of data flows
Secure boot
TPM
Boot loader +
Keys

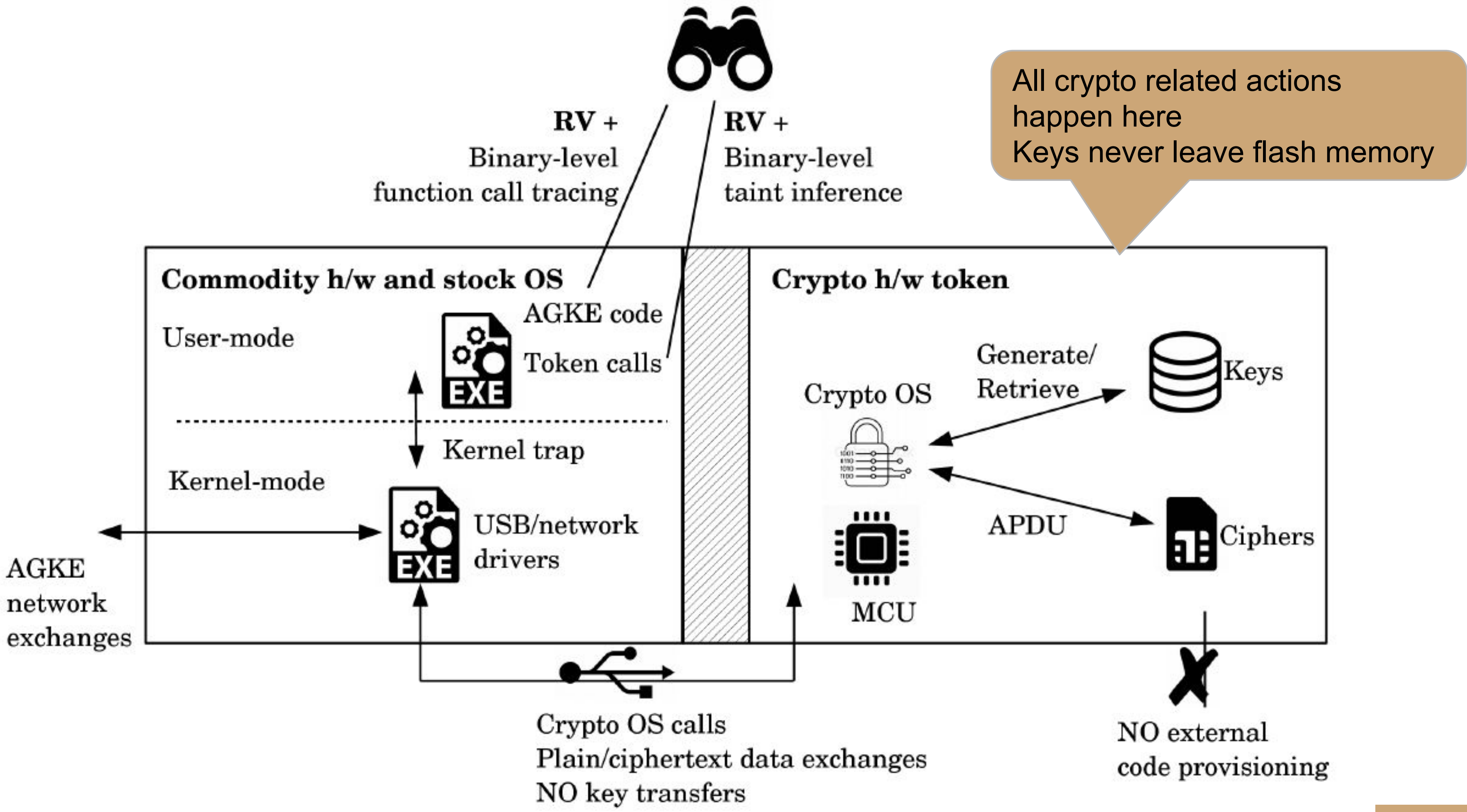
Trusted isolated hardware - avoid hardware threats






Highly restricted+monitored communication to the outside world - Avoiding leaks, malware, etc

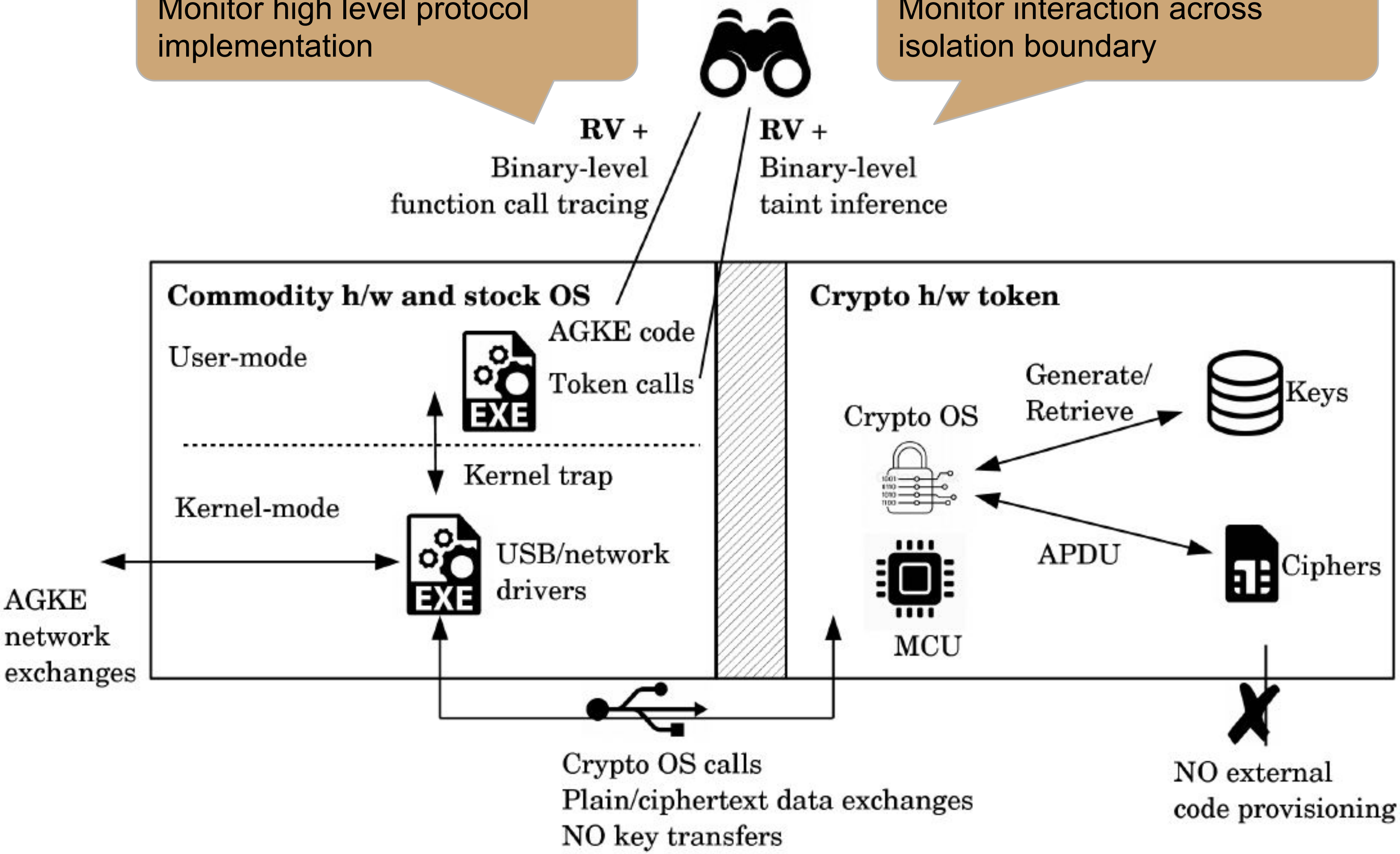
# Applying Trusted Execution Environment to AGKE



All crypto related actions happen here
Keys never leave flash memory
RV +
Binary-level
function call tracing
RV +
Binary-level
taint inference
Commodity h/w and stock OS
User-mode
AGKE code
Token calls
Kernel trap
Kernel-mode
USB/network
drivers
AGKE
network
exchanges
Crypto h/w token
Crypto OS
Generate/
Retrieve
Keys
APDU
Ciphers
MCU
Crypto OS calls
Plain/ciphertext data exchanges
NO key transfers
NO external
code provisioning

Monitor high level protocol implementation

Monitor interaction across isolation boundary



# What can go wrong at runtime?

...but in practice is far from enough

(High le Monitor 1 col
implementation

Monitor 2

Low level threats

By trusted execution env.

Hardware

The protocol implementation might deviate from the verified (theoretical) design

Medium level threats: Data leaks, malware, etc

and invalid pointer references

Can hardware be trusted?

# Overheads concerns

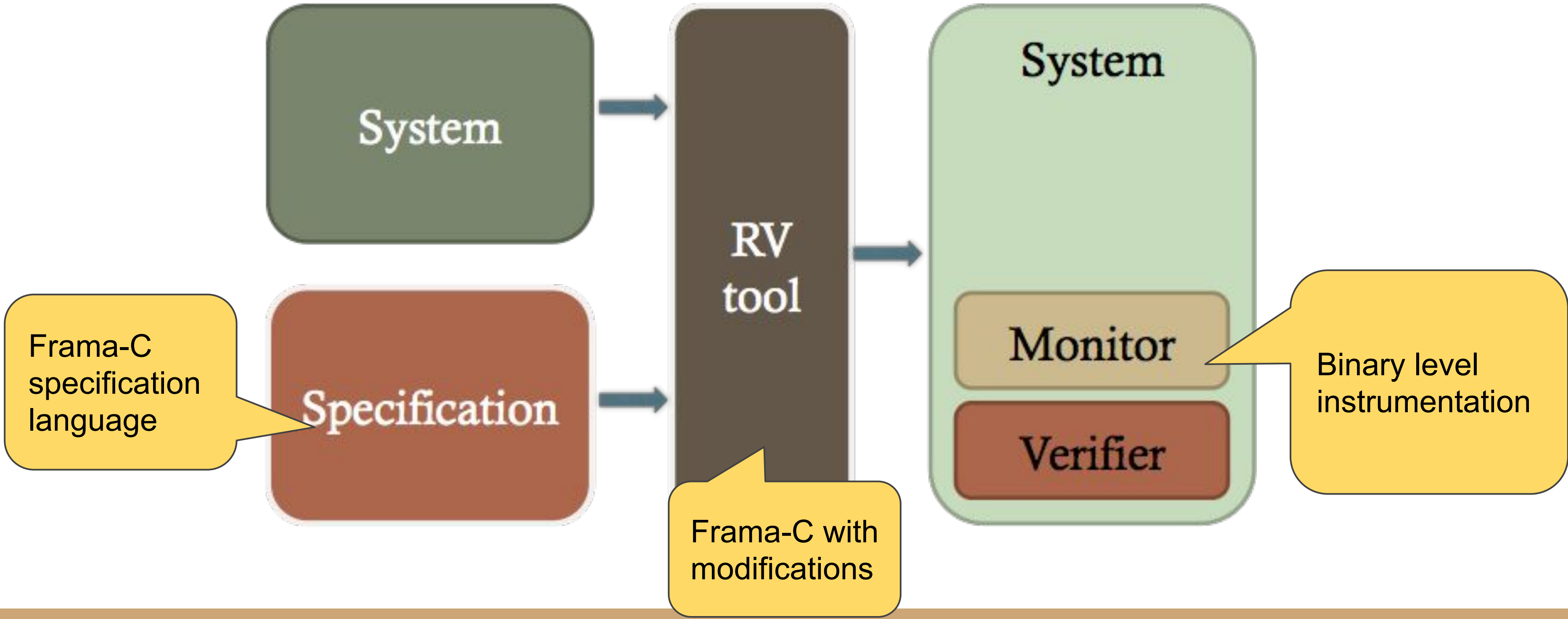
Instrument at binary level

- Enables full optimisation

Taint tracking is expensive

- Taint inference as an optimisation (Trades precision with efficiency)

# Future Work



System
Specification
RV tool
System
Monitor
Verifier
Frama-C specification language
Frama-C with modifications
Binary level instrumentation