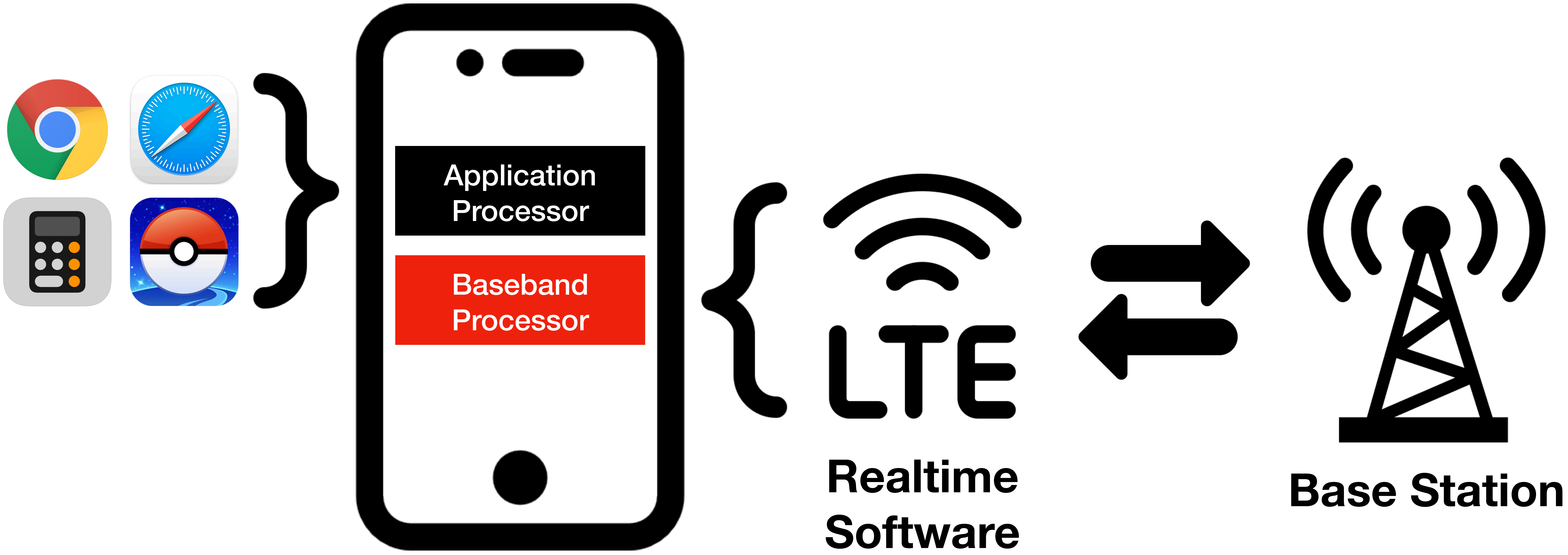
BaseComp:
A Comparative Analysis for Integrity Protection in Cellular Baseband Software

Eunsoo Kim*†, **Min Woo Baek*†**, CheolJun Park†, Dongkwan Kim‡, Yongdae Kim†, Insu Yun†

†KAIST, ‡Samsung SDS

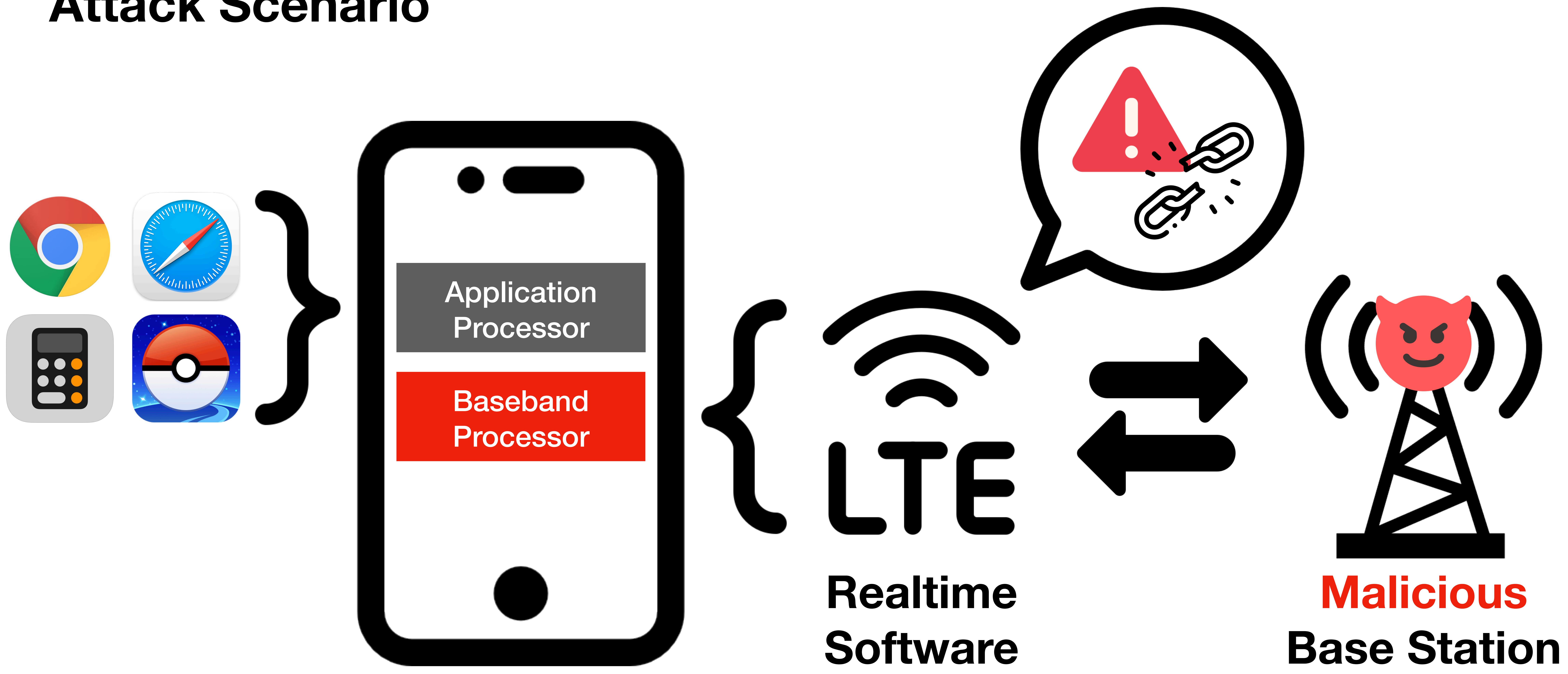
Baseband Software

Cellular Network Architecture



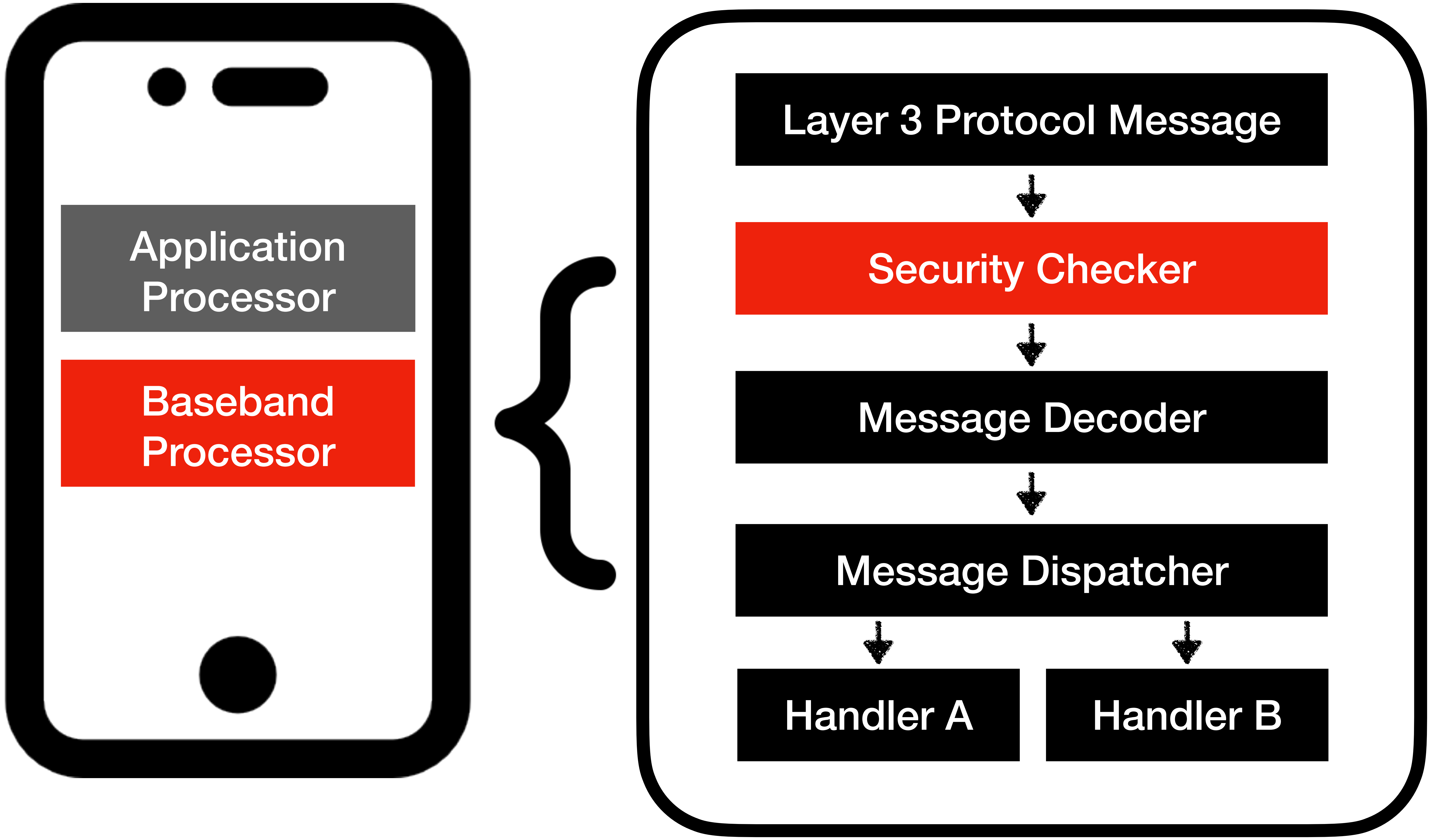
Baseband Software

Attack Scenario



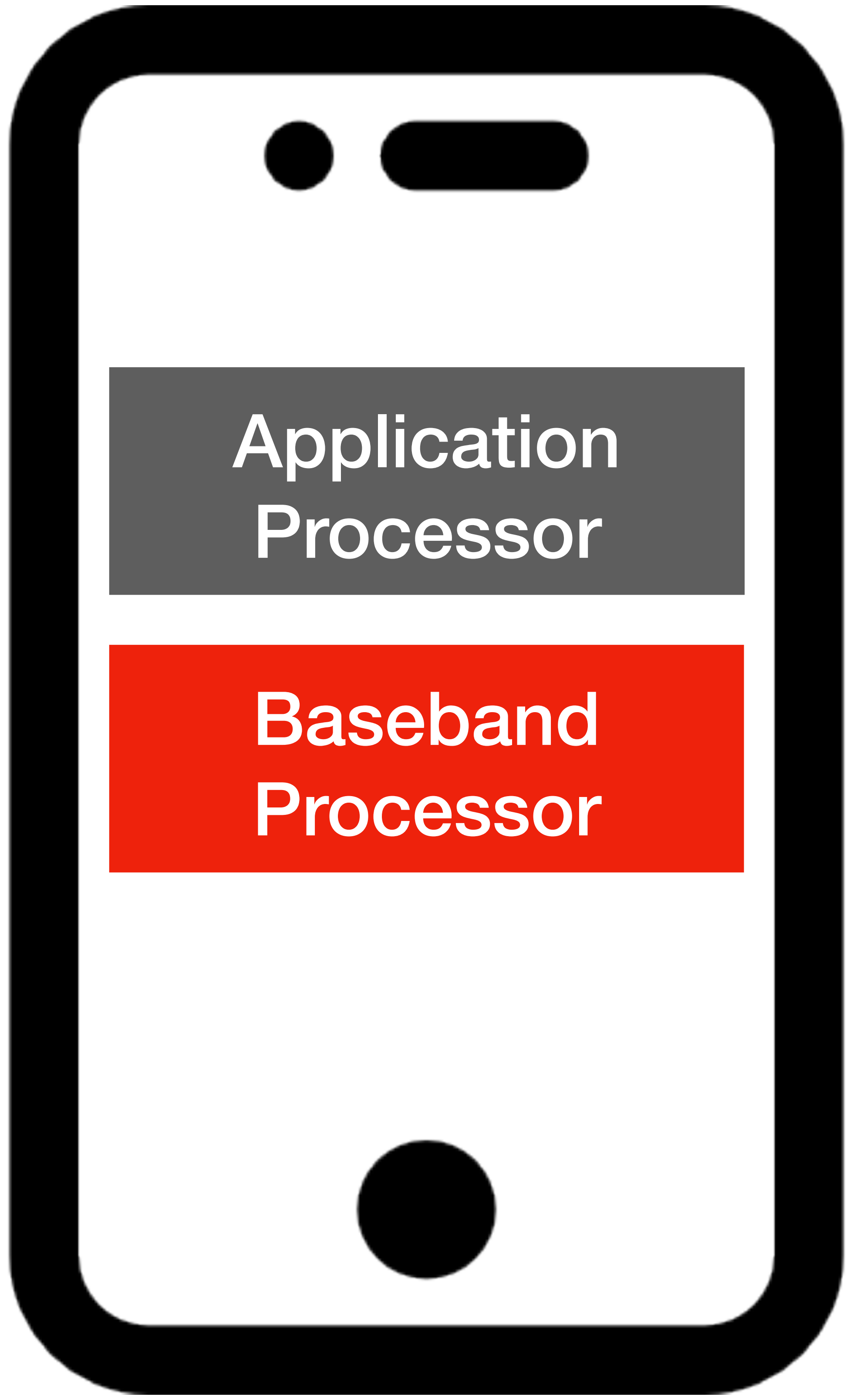
Baseband Software

Message Processing Logic



Baseband Software

Challenges



- **Obscurity**
  - Vendors don't release the details
- **Large Binary Size**
  - The baseband software has to implement documents of n*100 pages

Motivation

Existing Approaches

- **Dynamic Analysis**
  - DoLTEst (Security'22), Firmwire (NDSS'22)
  - Sends messages and observes responses from real or emulated devices
  - Has to restrict the search space leading to missing bugs
- **Static Analysis / BaseSpec (NDSS'21)**
  - Limited to message decoding and fails to analyze integrity protection
  - The vast size and obscurity causes highly resource-consuming manual analysis

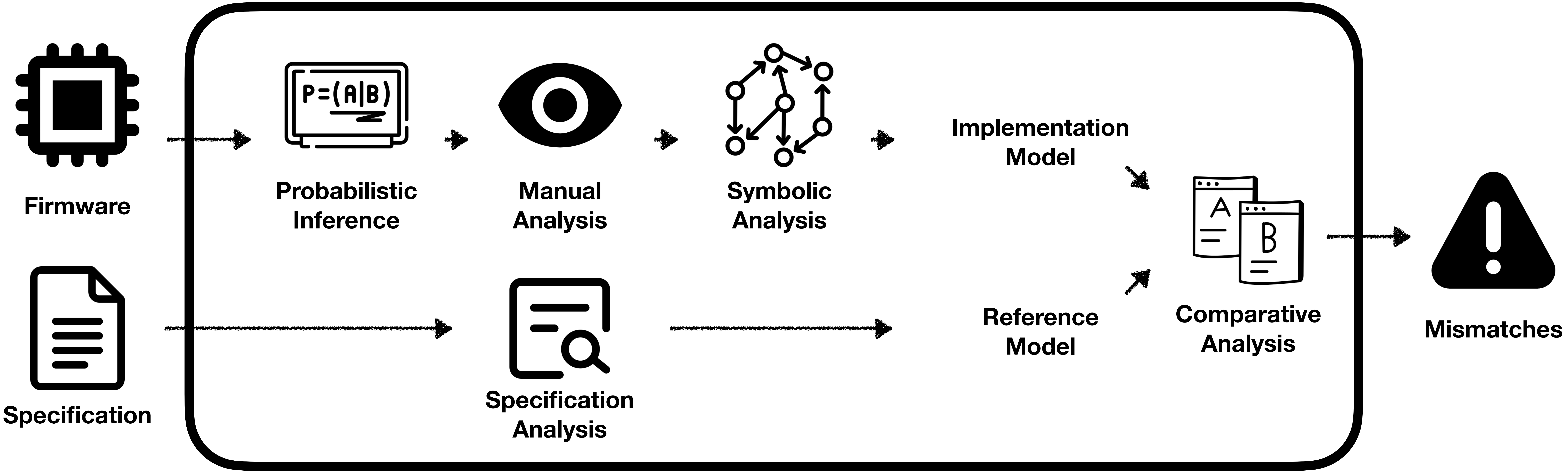
Motivation

Our Approach

- **Static Analysis**
  - Without having to restrict the search space
- **Comparative Analysis**
  - Comparison with specification to uncover bugs in integrity protection
- **Probabilistic Inference**
  - Reduce the amount of manual effort needed

BaseComp

Overview



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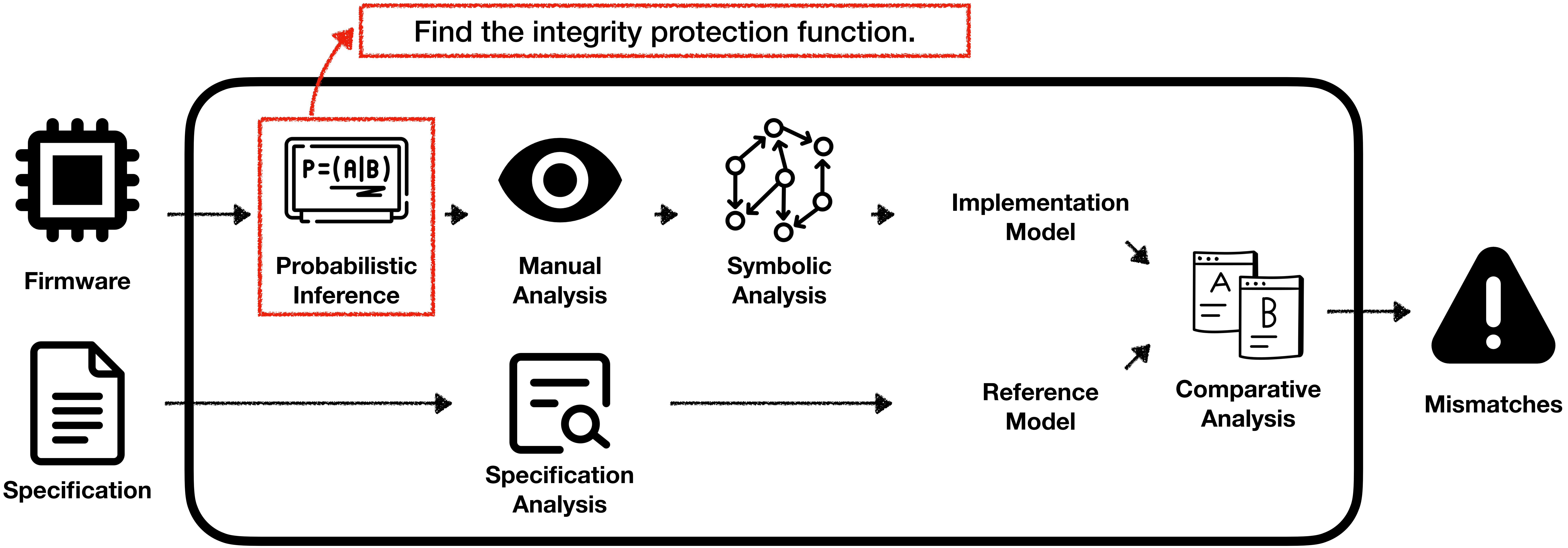
Probabilistic Inference



BaseComp

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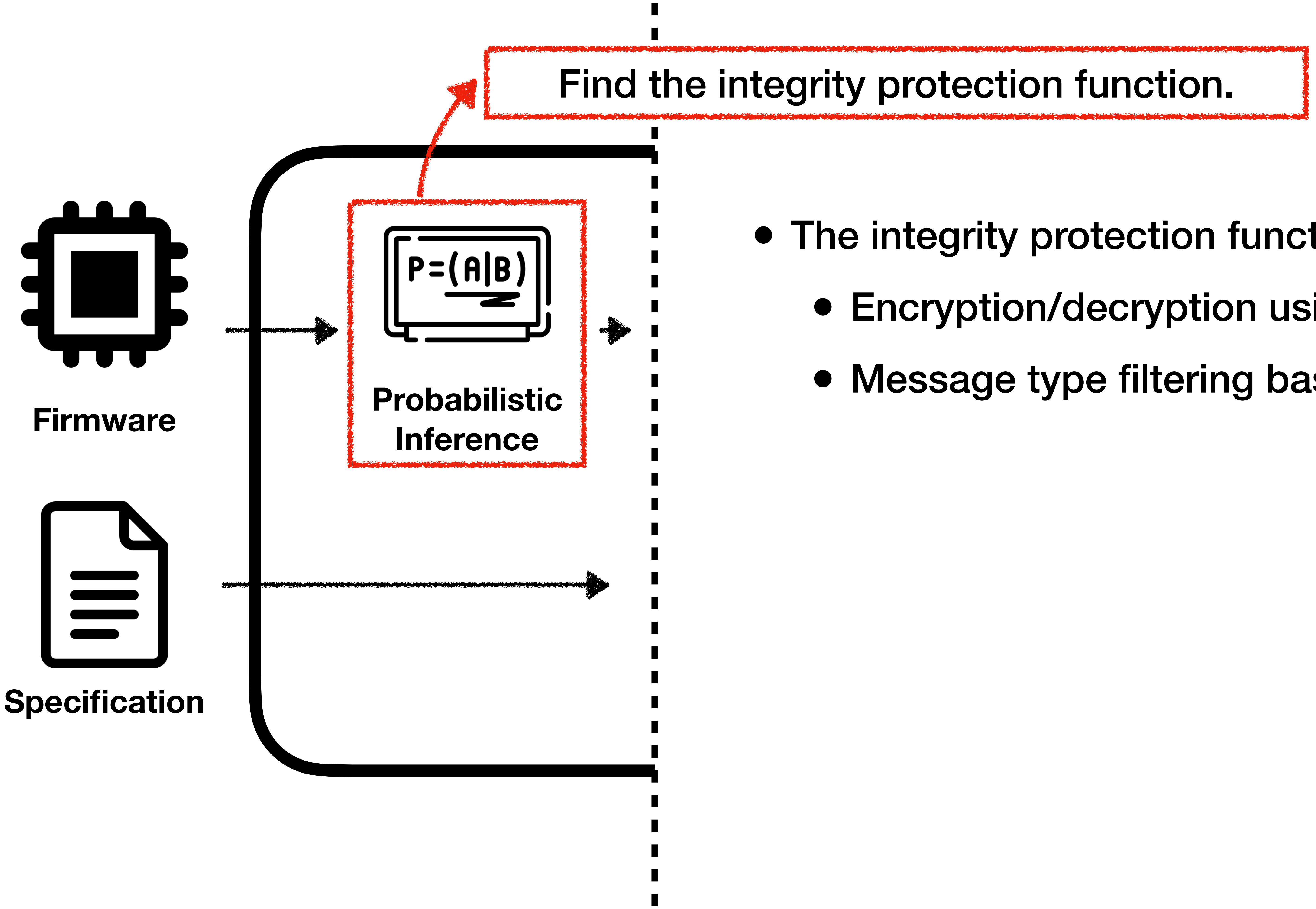
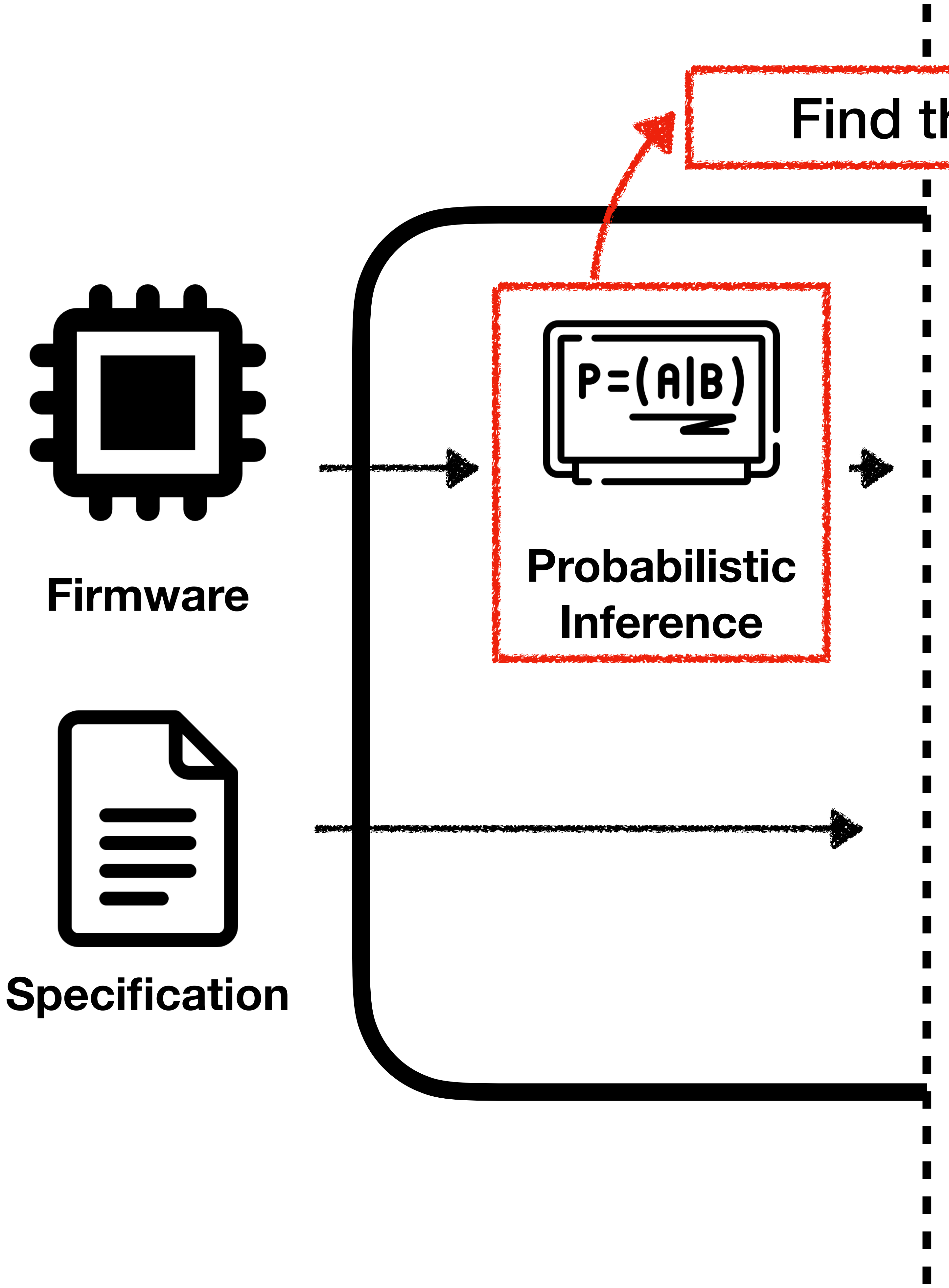


- The integrity protection function needs to have the following logics.
  - Encryption/decryption using AES/ZUC/SNOW3G
  - Message type filtering based on subclause 4.4.4.2 of TS 24.301

BaseComp

Probabilistic Inference



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  - Encryption/decryption using AES/ZUC/SNOW3G
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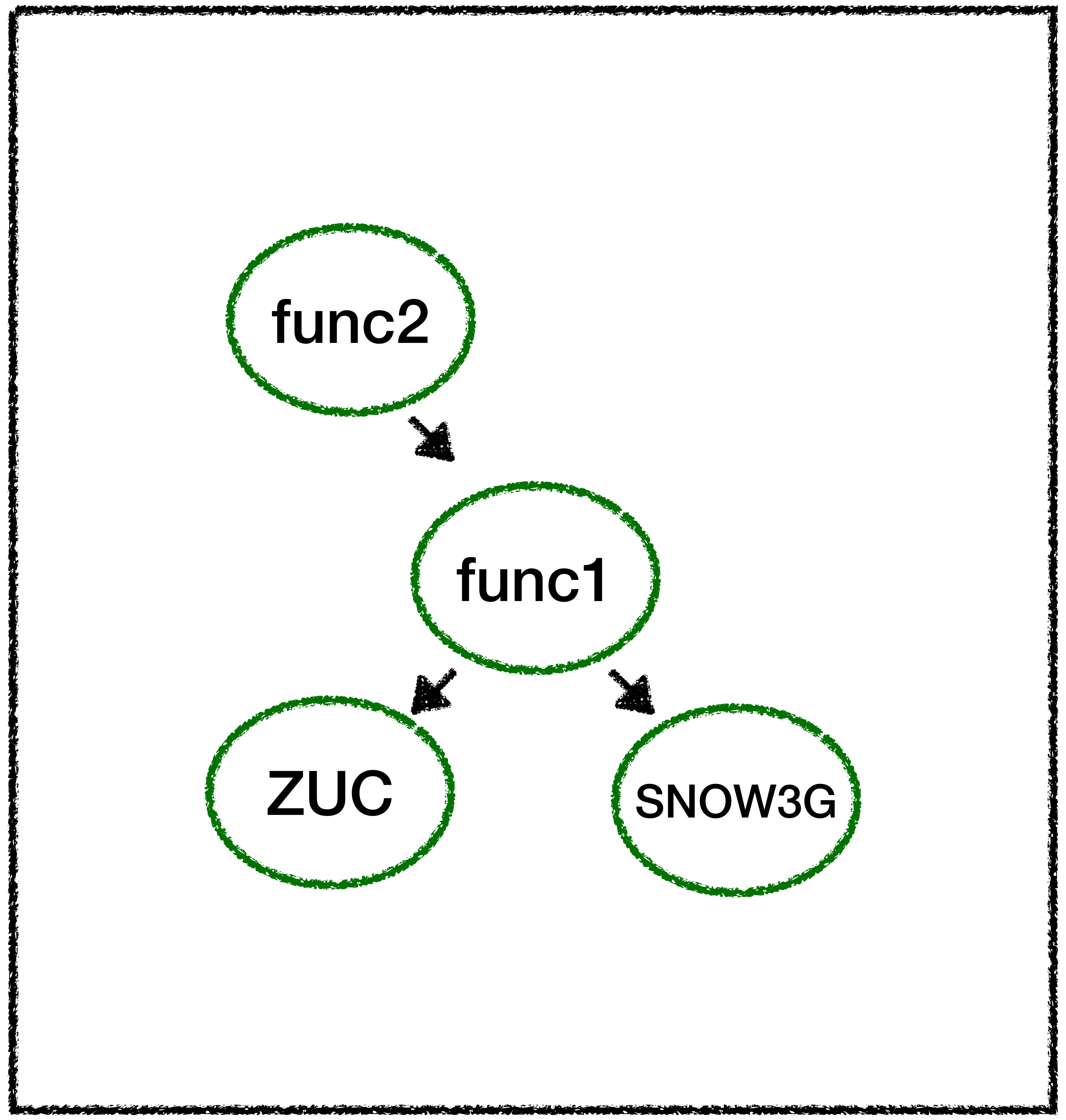
- Steps
  1. Identifying MAC functions.
  2. Identifying message type comparing functions.
  3. Putting it all together.

BaseComp

Probabilistic Inference

1. Identifying MAC functions.



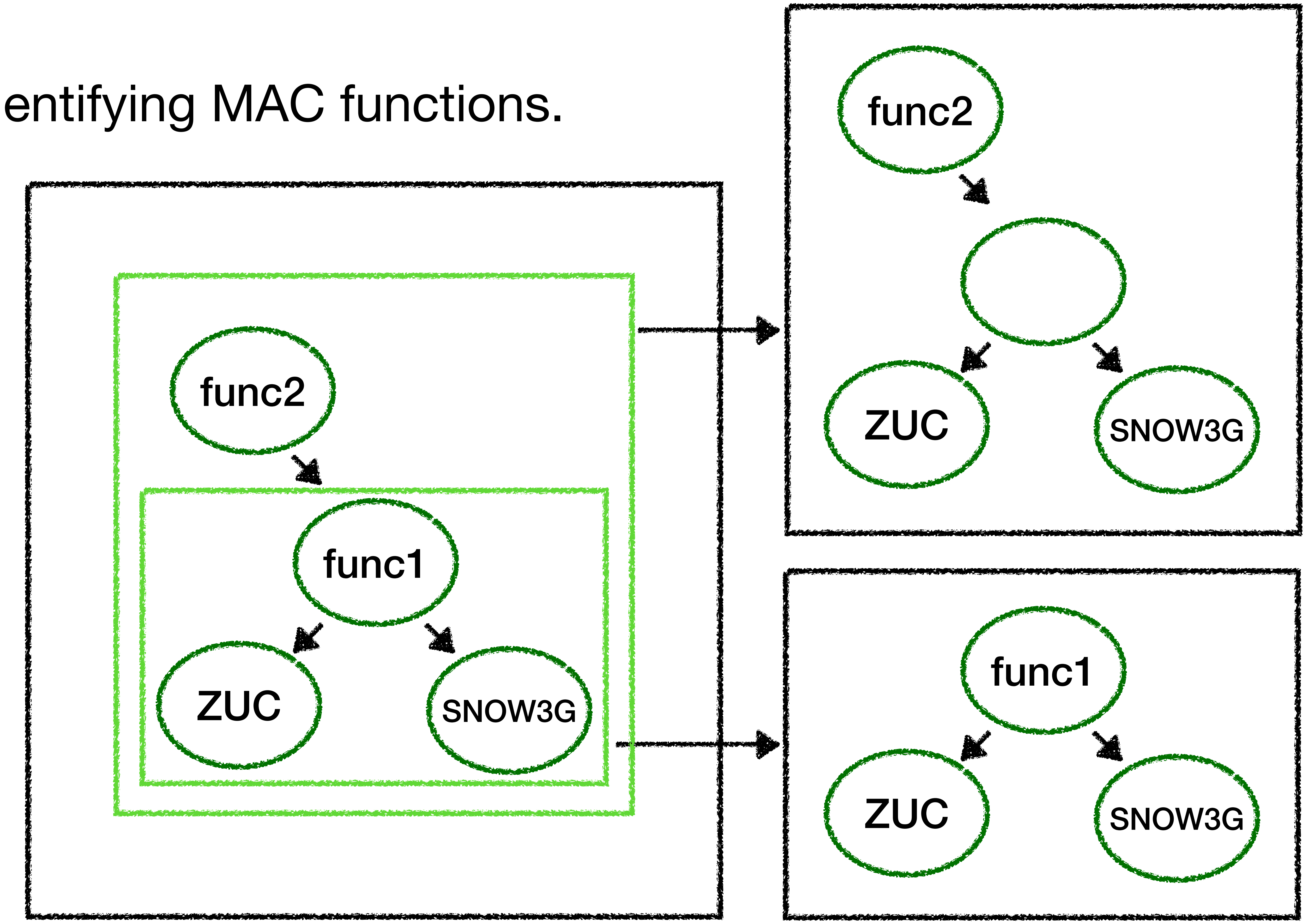
<Call Graph>

- **Cryptographic functions identified by magic constants (S-Box)**

BaseComp

Probabilistic Inference

1. Identifying MAC functions.



<Call Graph>

- Find common ancestors of cryptographic functions

BaseComp

Probabilistic Inference

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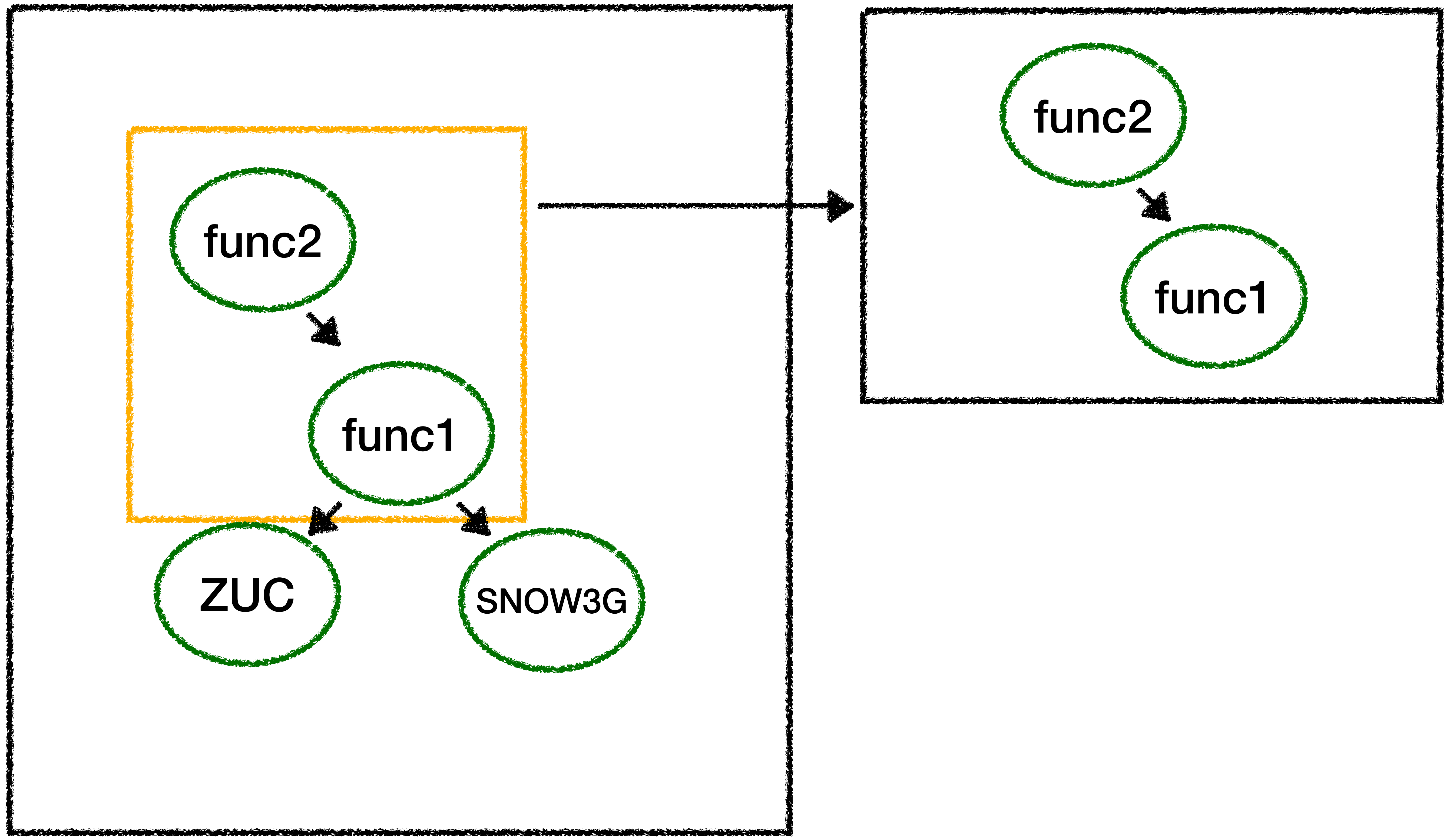

<Call Graph>

- Prioritize lower common ancestors

BaseComp

Probabilistic Inference

2. Identifying message type comparing functions.

4.4.4.2 Integrity checking of NAS signalling messages in the UE

Except the messages listed below, no NAS signalling messages shall be processed by the receiving EMM entity in the UE or forwarded to the ESM entity, unless the network has established secure exchange of NAS messages for the NAS signalling connection:

- EMM messages:
  - IDENTITY REQUEST (if requested identification parameter is IMSI);
  - AUTHENTICATION REQUEST;
  - AUTHENTICATION REJECT;
  - ATTACH REJECT (if the EMM cause is not #25);
  - DETACH ACCEPT (for non switch off);
  - TRACKING AREA UPDATE REJECT (if the EMM cause is not #25);
  - SERVICE REJECT (if the EMM cause is not #25).

```
{0x55, 0x44, 0x4B, 0x4E, 0x52, 0x54, 0x46}
```

NOTE: These messages are accepted by the UE without integrity protection, as in certain situations they are sent by the network before security can be activated.

BaseComp

Probabilistic Inference

2. Identifying message type comparing functions.

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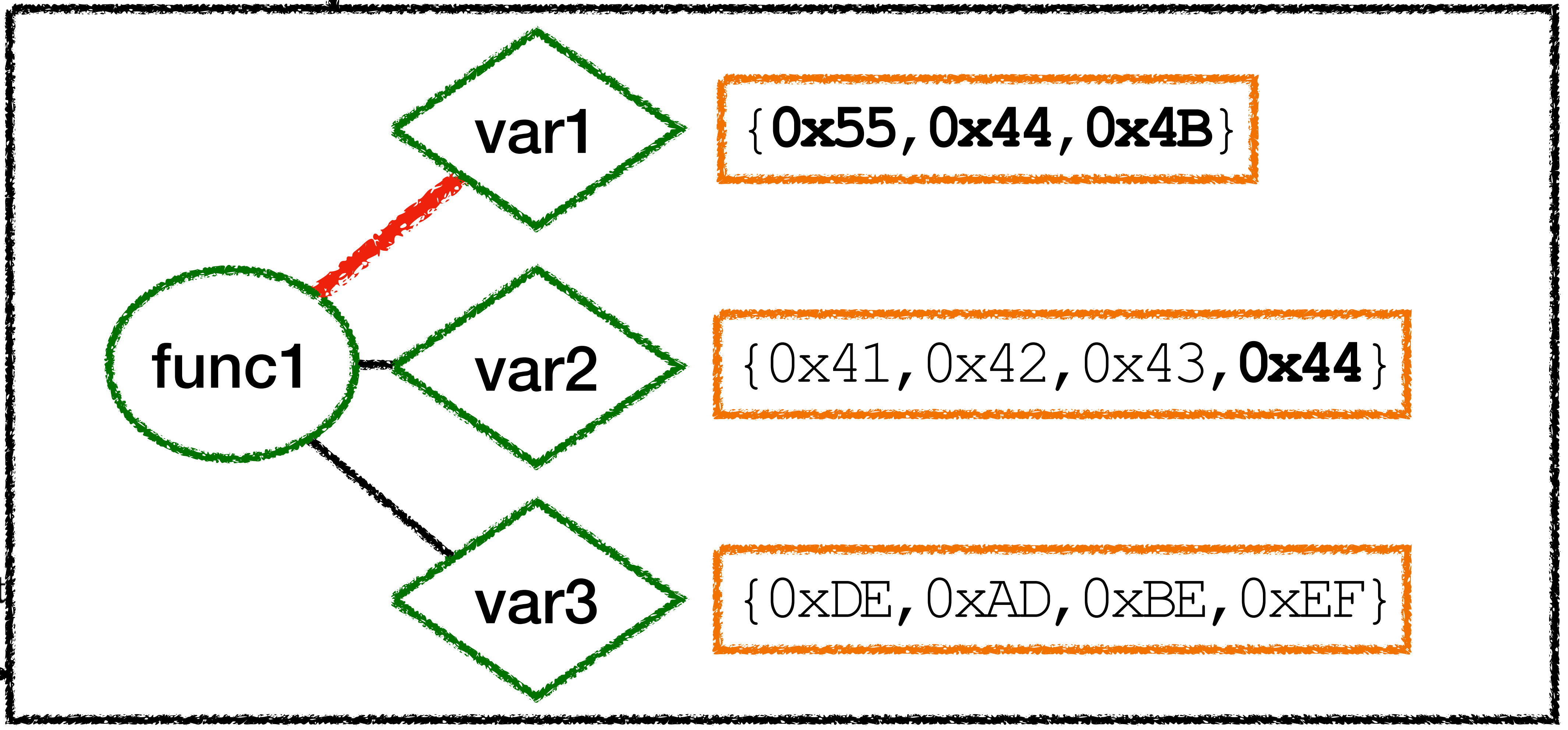
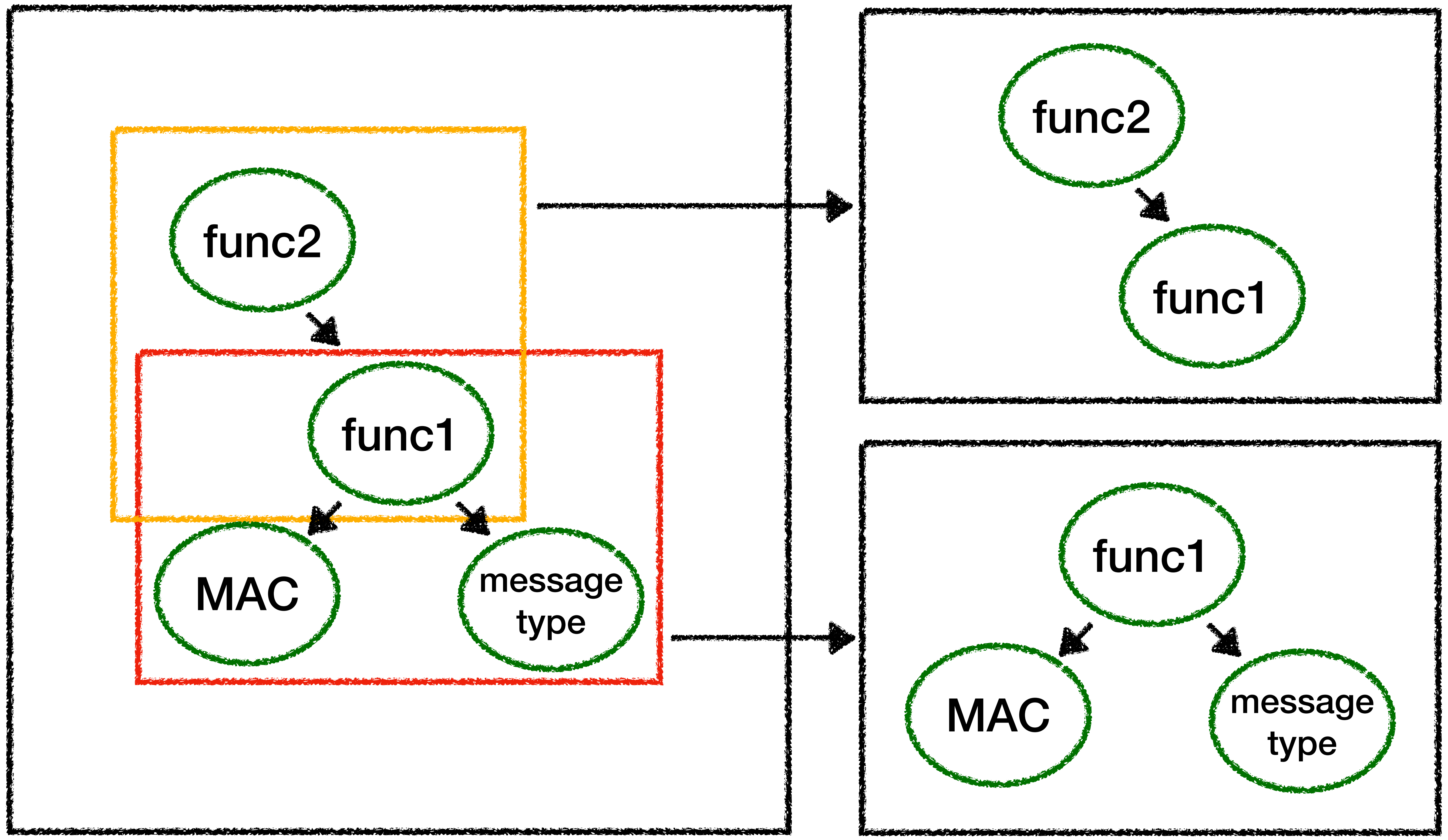


- **Iterate every function and its variables**

BaseComp

Probabilistic Inference

3. Putting it all together.

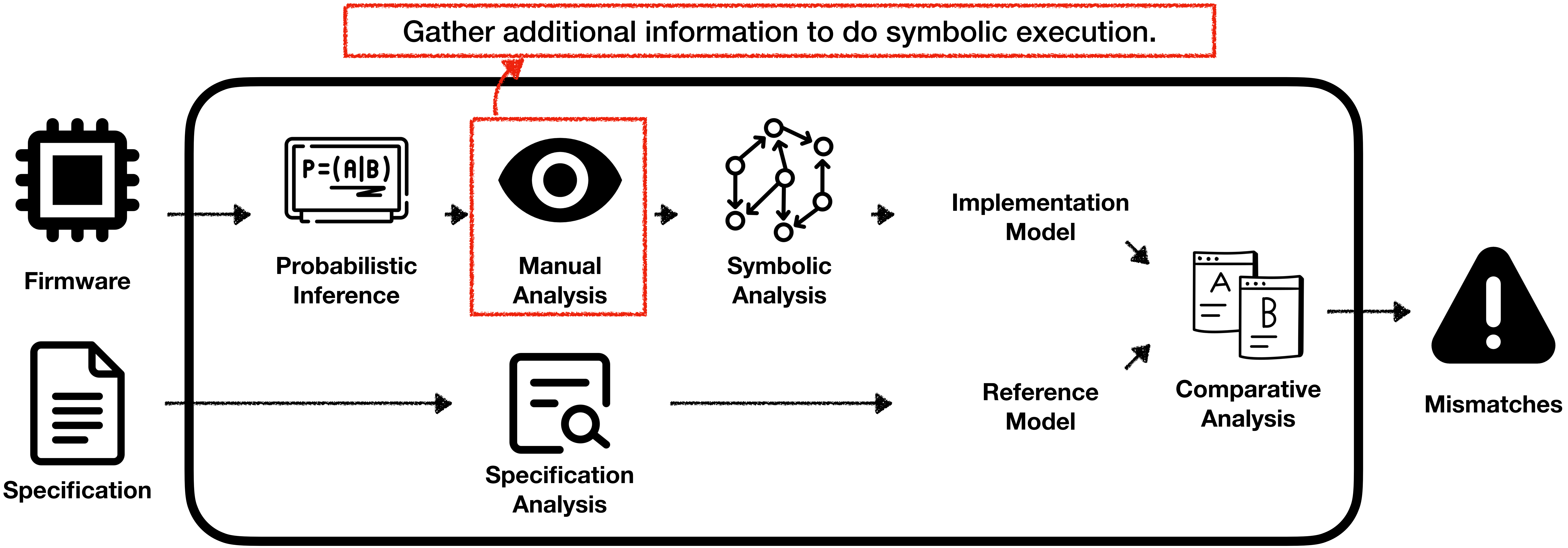


<Call Graph>

- Prioritize lower common ancestors
- Find common ancestors of
  - MAC function
  - Message type comparing function

BaseComp

Manual Analysis



BaseComp

Manual Analysis

- Additional information about the firmware is required to process symbolic execution

```python
def symbolize(s, config):
  # Symbolizes a message buffer and a state variable
  msg_buf = s.solver.BVS('message_buffer', 32)
  s.regs.r0 = msg_buf

  sec_state = s.solver.BVS('security_state', 8)
  s.memory.store(config.security_state, sec_state)


def accepting(s, config):
  # Check if this return represents accepting a message
  return s.ret_val == 1
```

- **Vendor-specific analysis module**
  - How to symbolize variables
  - How to decide if a message is accepted
- **Required per-vendor**

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- **Required per-vendor**

```yaml
analysis:          ./analysis_samsung.py

# Functions for analysis
integrity_func:         0x4150AECD
mac_validation_func:    0x4150A3D6
security_state:         0x429B27C4

# Functions to skip to avoid path explosion
skip_funcs:
    - 0x40CECC87
    - 0x4057F5FB
```

- **Firmware-specific configuration**
  - Integrity protection function address
  - MAC validation function address
  - Security state address
  - Deny-list of functions to prevent path explosion
- **Required per-firmware**

BaseComp

Manual Analysis

- Additional information about the firmware is required to process symbolic execution

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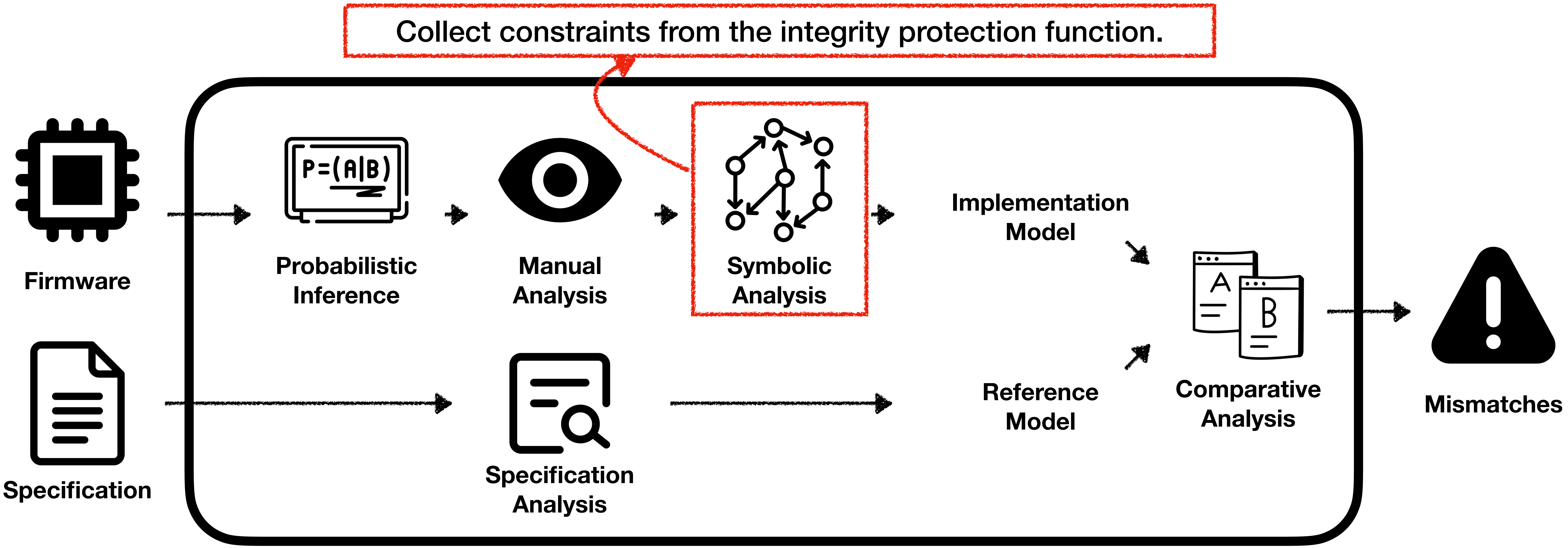
BaseComp

Symbolic Analysis



BaseComp

Symbolic Analysis

- Under-constrained symbolic execution on the integrity protection function.
- Collect constraints related to the message.

```
// A state variable for a security context.
SecState sec_state;

bool IntegrityProtection(void* message) {
    // Returns true if the 'message' is valid to be accepted.
    if (CheckHeader(message)
        && (!IsProtected(message) || CheckSeq(message))
        && (!IsProtected(message) || ValidateMac(message))) return true;
    else
        return false;
}

bool CheckHeader(void* message) {
    uint8_t sec_hdr_type = GetSecHdrType(message);
    uint8_t msg_type = GetMsgType(message);

    if (sec_state == SECURE) {

        if (sec_hdr_type == 0)
            return false;
        else if (sec_hdr_type != 0 && sec_hdr_type <= 3)
            return true;
        else
            return false;

    } else { // INSECURE
        if (sec_hdr_type == 0) {
            switch (msg_type) {
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                case 0x44;
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                    return true;
                default:
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            }
        }
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BaseComp

Symbolic Analysis

- Under-constrained symbolic execution on the integrity protection function.

- Collect constraints related to the message.

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BaseComp

Symbolic Analysis

- Under-constrained symbolic execution on the integrity protection function.
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sec_state == SECURE

+

0 < sec_hdr_type <= 3

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BaseComp

Symbolic Analysis

- Under-constrained symbolic execution on the integrity protection function.
- Collect constraints related to the message.

sec_state == SECURE

+

0 < sec_hdr_type <= 3

sec_state != SECURE

+

sec_hdr_type == 0

+

msg_type in {0x55, ... , 0x46}

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BaseComp

Symbolic Analysis

- Under-constrained symbolic execution on the integrity protection function.
- Collect constraints related to the message.

sec_state == SECURE
+
0 < sec_hdr_type <= 3

sec_state != SECURE
+
sec_hdr_type == 0
+
msg_type in {0x55, ... , 0x46}

+

CheckSeq(message) == true && ValidateMac(message) == true

→ **Message is accepted!**

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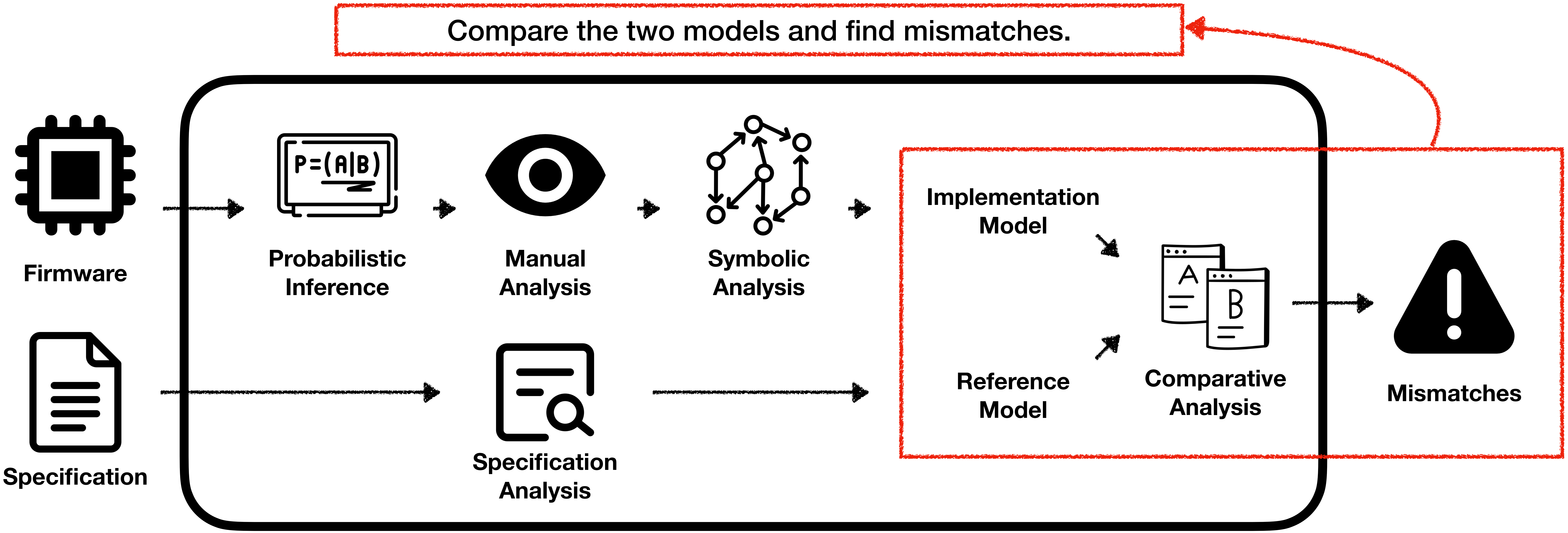
BaseComp

Comparative Analysis



Evaluation

Setup

- Research Questions
  1. How well can BaseComp find the integrity protection function?
  2. How effectively can BaseComp discover bugs?

- Dataset
  - 16 images (10, 5, 1 from Samsung, MediaTek, srsRAN respectively)
  - ARM, MIPS(with 16e2 extension), and x86 architecture

Evaluation

How well can BaseComp find the integrity protection function?

- Effectiveness

	G950	G955	G960	G965	G970	G975	G977	G991	G996	G998	Pro 7	A31	A31'	A03s	A145	srsran	AVG
Size(MB)	41.2	41.8	41.5	41.6	44.0	44.3	44.3	66.6	66.3	66.3	17.8	22.5	22.5	16.8	17.0	92.9	43.0
Number of funcs	64K	61K	74K	74K	92K	75K	92K	103K	108K	103K	48K	94K	94K	65K	65K	96K	82K
Rank	1	1	1	1	1	1	1	3	1	3	2	2	2	2	2	1	1.56

<The rank of the integrity protection function for each firmware>

Evaluation

How effectively can BaseComp discover bugs?

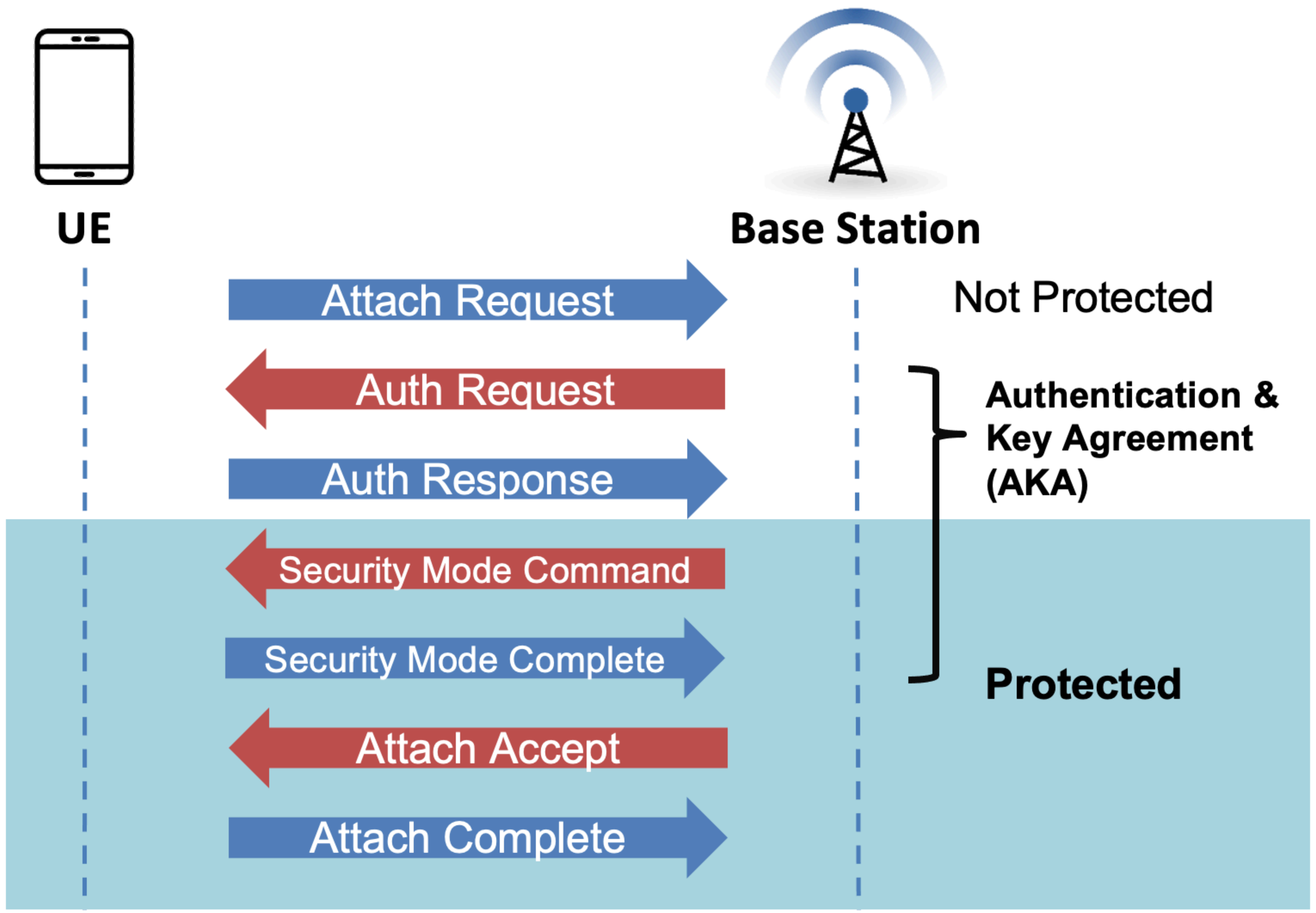
- Summary
  - 34 Mismatches
  - 29 True Positives
    - Classified to 15 types
  - 5 False Positives

	Samsung	MediaTek	srsRAN	Total
Mismatches	9	10	15	34
False Positives	1	3	1	5
True Positives	8	7	14	29

Case Study

NAS AKA Bypass Vulnerability

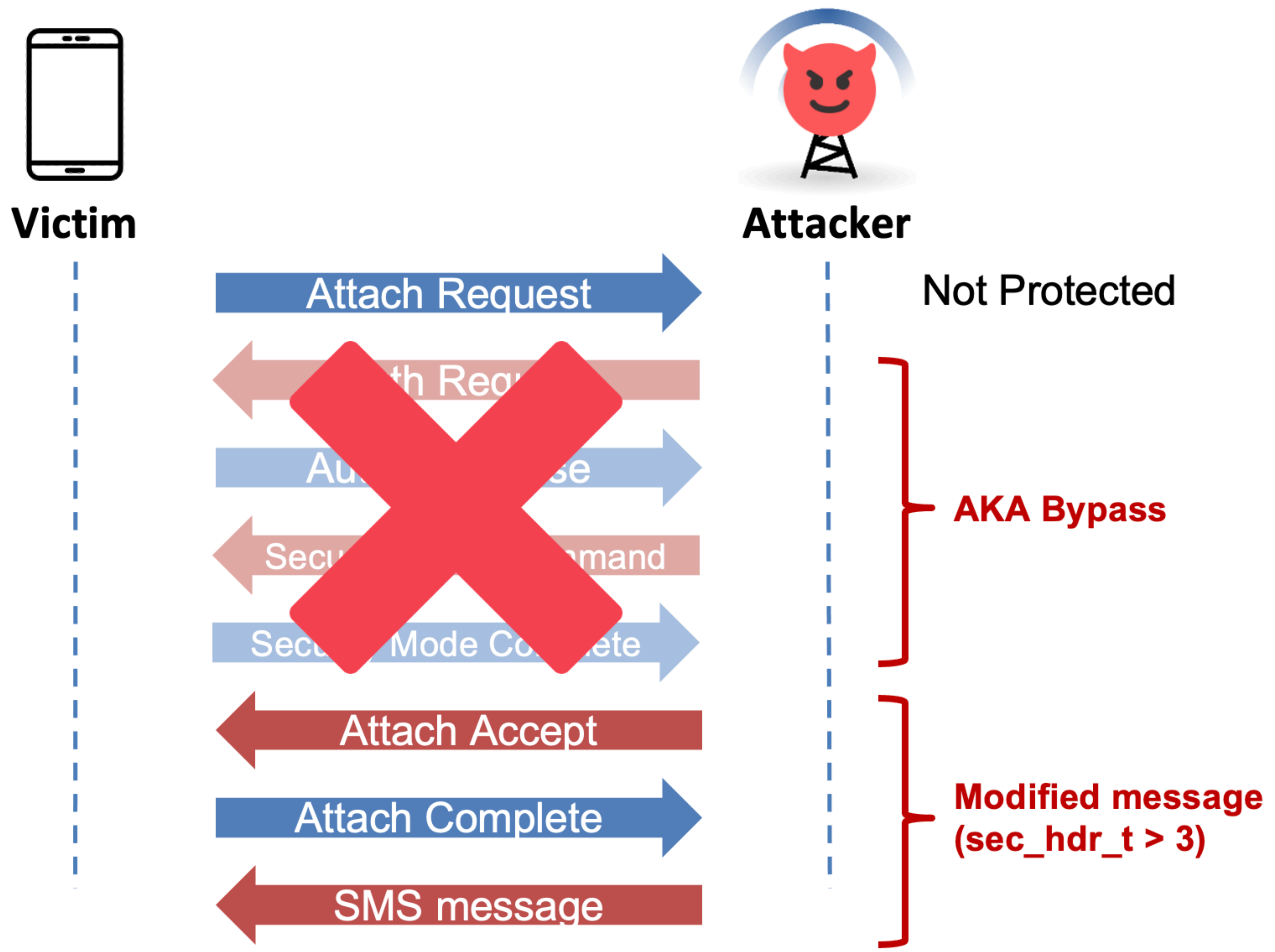
- NAS Authentication and Key Agreement



Case Study

NAS AKA Bypass Vulnerability

- NAS Authentication and Key Agreement bypass
  - *Attach Accept* message to connect to malicious base station
  - Send arbitrary NAS messages in plaintext
    - Gather IMEI with *Identity Request* message
    - Modify time with *EMM Information* message
    - ...



Case Study

NAS AKA Bypass Vulnerability

- NAS Authentication and Key Agreement bypass

sec_state != SECURE

+

sec_hdr_type != 0

+

sec_hdr_type > 3

Message is accepted!

(regardless of any other element of the message)

```
// A state variable for a security context.
SecState sec_state;

bool IntegrityProtection(void* message) {
    // Returns true if the 'message' is valid to be accepted.
    if (CheckHeader(message)
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        && (!IsProtected(message) || ValidateMac(message))) return true;
    else
        return false;
}

bool IsProtected(void* message) {
    uint8_t sec_hdr_type = GetSecHdrType(message);
    return sec_hdr_type != 0 && sec_hdr_type <= 3;
}

bool CheckAllowableInNonSecure(void* message) {
    // Returns true if the 'message' is specified
    // as exceptions in TS 24.301.
    ...
}

bool CheckHeader(void* message) {
    uint8_t sec_hdr_type = GetSecHdrType(message);

    if (sec_state == SECURE) { ... }

    else { // INSECURE
        if (sec_hdr_type == 0)
            return CheckAllowableInNonSecure(message);
        else {
            // BUG: In the INSECURE state,
            // this function returns true
            // if sec_hdr_type is non-zero yet invalid.
            return true;
        }
    }
}
```

Case Study
NAS AKA Bypass Vulnerability

- Delivering an arbitrary SMS message
    - Sender
        - 010-1000-1100
    - Time
        - January 3rd, 2030
    - SMS Data
        - Hello World!! from 2030

Conclusion

- **Proposed a novel semi-automatic approach to analyze the integrity protection.**
  - Probabilistic inference + Comparative analysis
- **Found 29 bugs from Samsung, MediaTek and srsRAN images.**
  - Including critical NAS AKA bypass vulnerabilities.

Thank You!