Requirements Testing and Verification for Smart Systems Through Systematic Software Analysis

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Smart end systems keep emerging

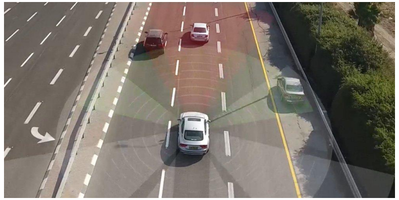
- Communication & information acquisition
  - Smartphone, wearable, IoT devices
- Transportation & mobility
  - Autonomous vehicle (AV)

Smartphone

Autonomous Vehicle

Key requirements

- **Performance** requirements
  - High mobility
  - Dynamic runtime
- **Security** requirements
  - Software complexity
  - Multi-party contribution
- **Safety** requirements
  - Driving safety logic in AV software



Thesis research goal

- **My thesis research**: Develop systematic software analysis approaches for testing and verifying key ***performance***, ***security*** and ***safety*** requirements of smart end systems
    - ***Static program analysis*** => completeness guarantee
    - ***Runtime profiling*** => capturing runtime dynamics

Thesis statement

Systematic software analysis approaches based on *static program analysis* and *runtime profiling, with domain-specific customization*, can lead to effective testing and verification of key *performance*, *security* and *safety* requirements for smart system software

Thesis work overview

Part I: Performance requirement testing and noncompliance diagnosis for mobile apps

Part II: Security vulnerability detection and mitigation in AV software systems

Part III: Self-driving safety requirement verification for AV software

Thesis contribution

- Performance requirement testing & problem diagnosis
  - **Thesis contribution**: *low-overhead, cross-layer* runtime profiling and performance diagnosis for smartphone systems
- Security and safety requirement verification
  - **Thesis contribution**: the first to apply static analysis for systematic discovery & mitigation of *new vulnerability* and verification of *safety requirement* for AV software systems

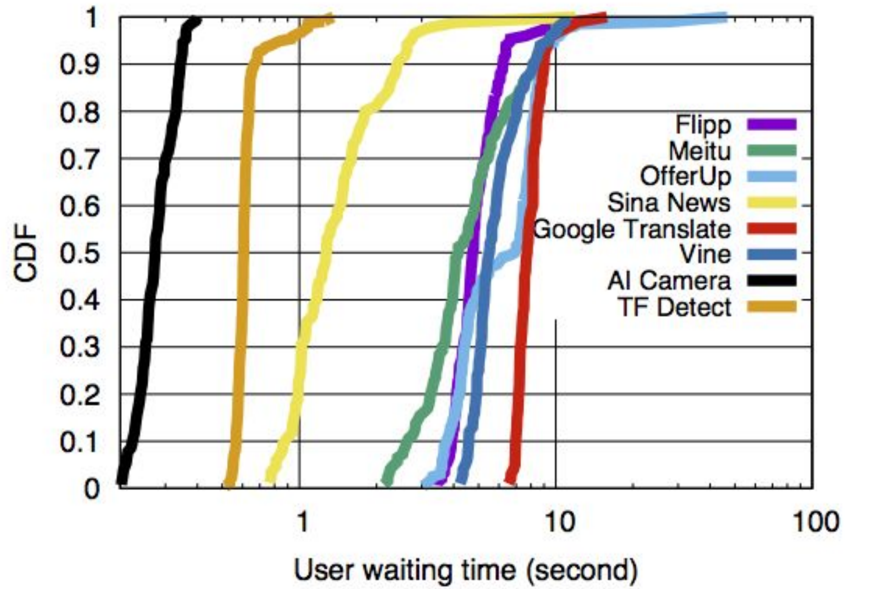
Part I: A Systematic, Cross-Layer Performance Diagnosis Framework for Mobile Platforms

- Platform support for performance requirement validation
- Runtime profiling and performance diagnosis

PerfProbe: A Systematic, Cross-Layer Performance Diagnosis Framework for Mobile Platforms. In MOBILESoft'19.

Background

- Unpredictable performance degradation violates the performance requirement for smartphone apps
  - 100 popular apps
  - Tail latency: **2~8x increase**

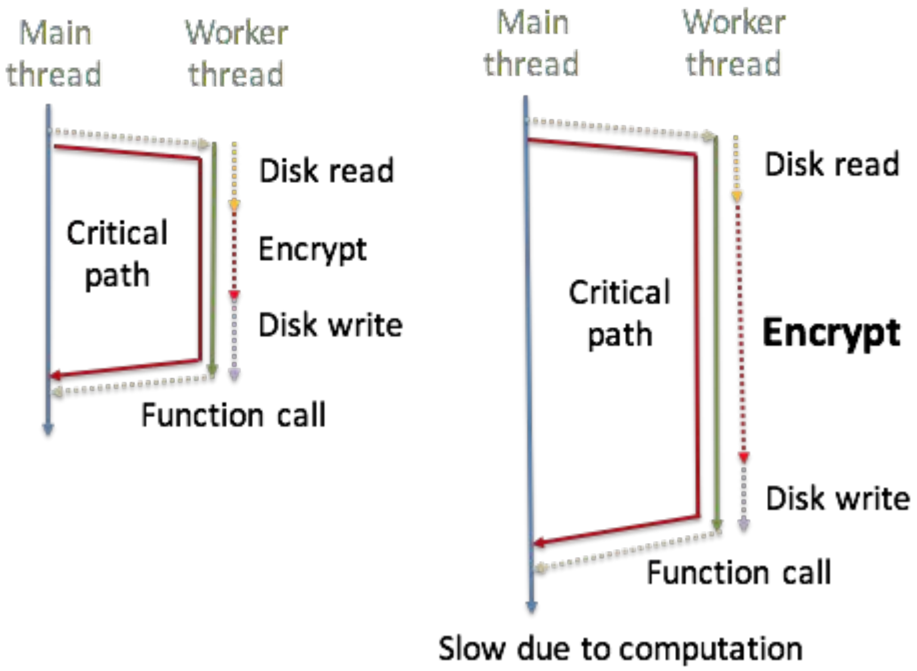


Contribution

- Profiling and ***associating app and system-layer runtime events*** can lead to
  - Holistic, cross-layer insights to better pinpoint the root cause of performance degradation
    - Built a ***low-overhead***, ***cross-layer*** performance profiling and diagnosis framework, PerfProbe, for mobile platforms
    - Existing work, e.g., AppInsight [OSDI ‘12], Panappticon [CODES'13], focusing on single-layer runtime profiling

Why cross-layer profiling

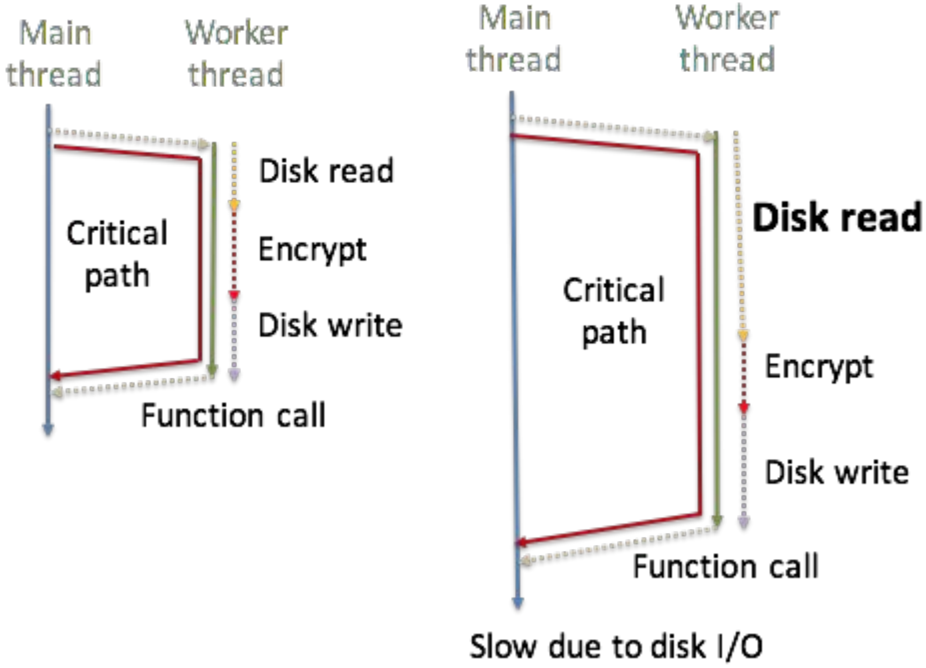
- Motivating example: encrypt a file on SD card



Performance degradation due to slowdown in **Encrypt**

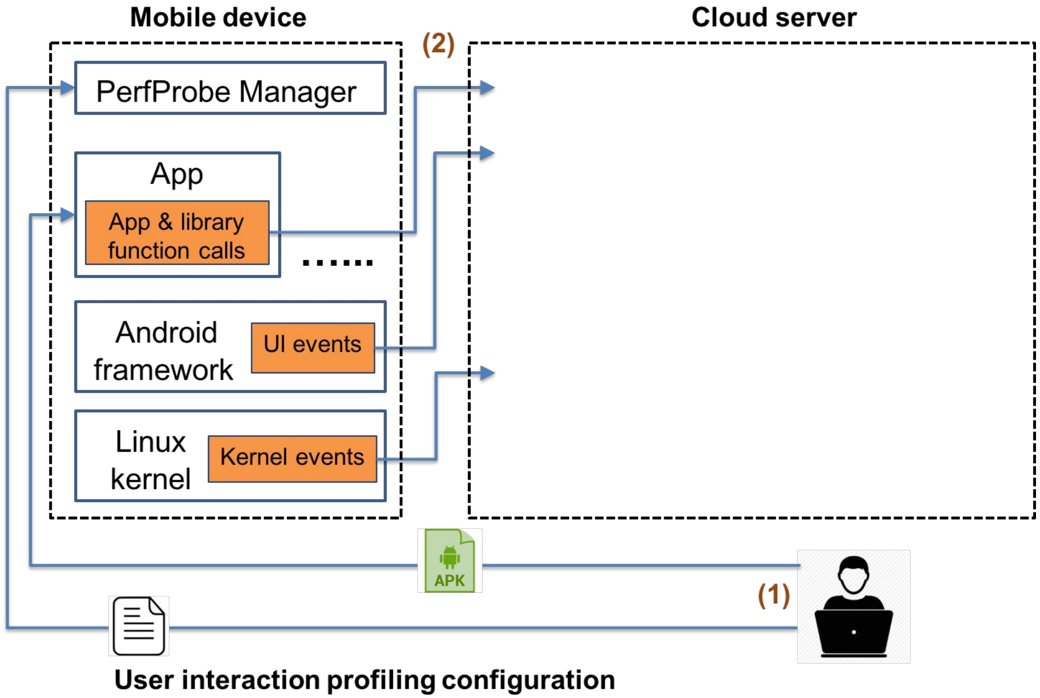
Why cross-layer profiling

- Motivating example: encrypt a file on SD card



Performance degradation due to slowdown in **Disk read**

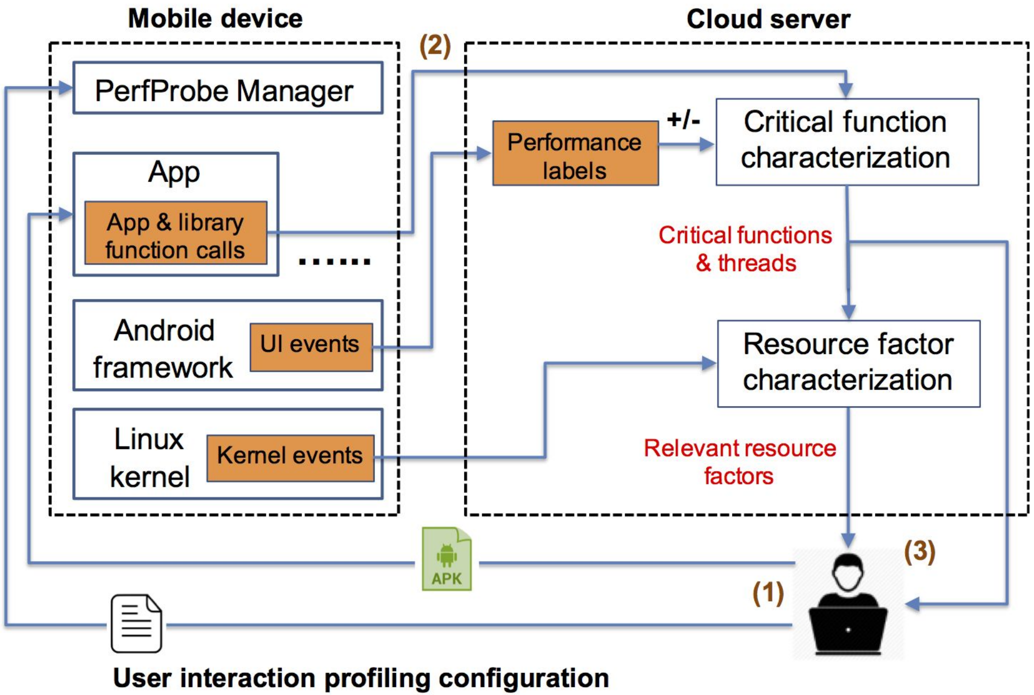
PerfProbe overview



On-device: runtime **performance monitoring** and profiling

1. App's call stack
2. OS event trace

PerfProbe overview



On-device: runtime **performance monitoring** and profiling

1. App's call stack
2. OS event trace

Server-side: cross-layer trace analysis for **problem diagnosis**

Experiment results

- Cross-layer profiling incurs < 3.5% increase of delay
  - Android's built-in profiling incurs 3-22% increase
- Usefulness of diagnosis findings
  - Guiding performance optimizing solutions to reduce latency of 6 popular apps by 32-86%
- Findings acknowledged by iNaturalist developer
  - Improve the response of a key interaction with **10x speedup**
  - Developer has **adopted our fixing suggestion** [link]

Conclusion (Part I)

- ***The first to design a low-overhead, cross-layer profiling and performance diagnosis framework*** for mobile platforms
- Improved performance of 6 popular Android apps using PerfProbe's diagnosis findings

Part II: Detecting and Mitigating Publish-Subscribe Overprivilege for Autonomous Vehicle Systems

- First characterization of overprivilege in AV systems
- Static analysis tool for systematic detection and mitigation of overprivilege

Autonomous vehicle software systems

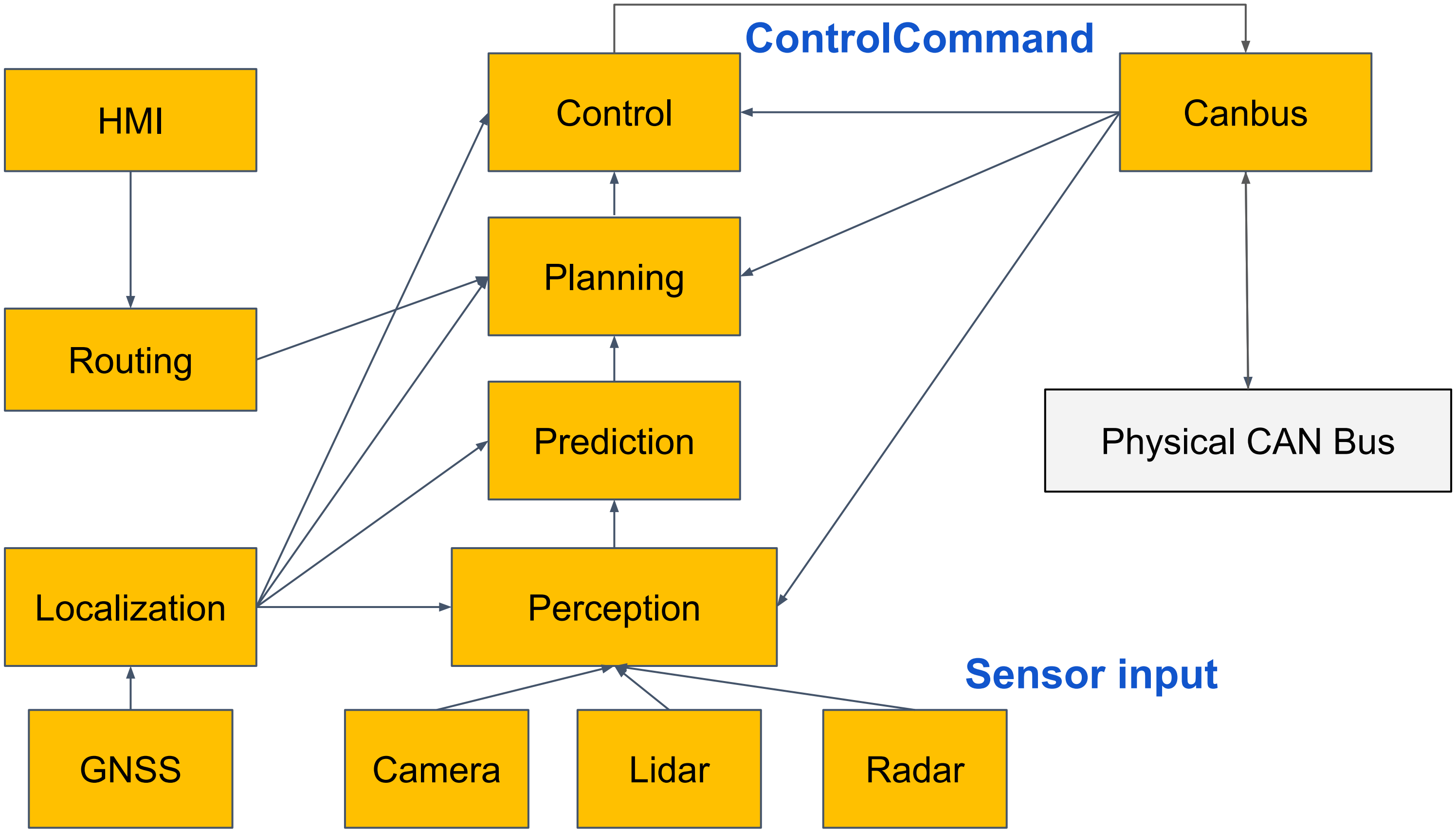
- *Robot Operating System* (ROS) middleware
  - Commonly used in various autonomous systems (e.g., AVs, drones, robots, etc.)

- ROS-based open-source AV platforms

AutoWare

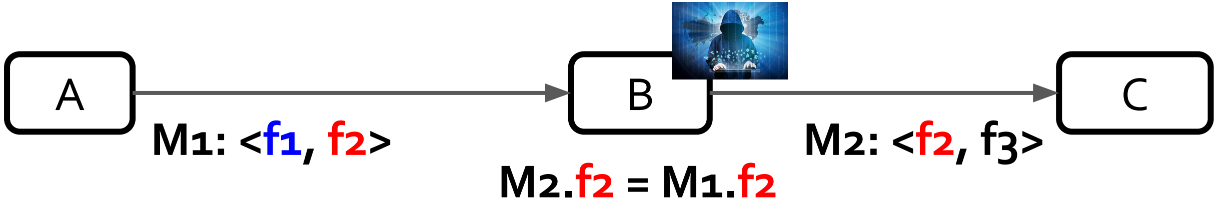
apollo

Publish-subscribe messaging in AV systems

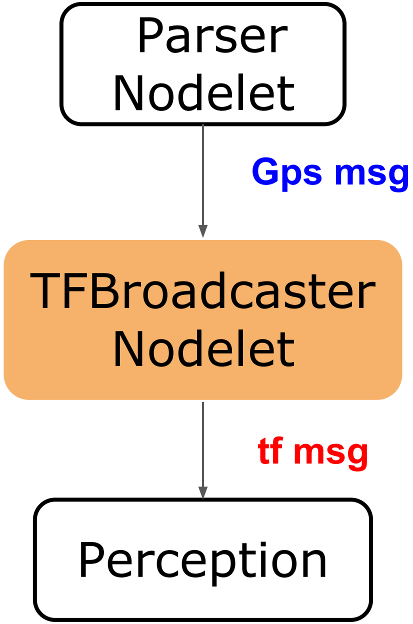


Publish-subscribe overprivilege characterization

- Subscriber-side overprivilege
  - Certain fields in a subscribed message are ***not read*** => ***over-granted read permission***
- Publisher-side overprivilege
  - Certain fields in a published message are ***not written*** by publisher => ***over-granted write permission***



Overprivilege in Baidu Apollo & Autoware



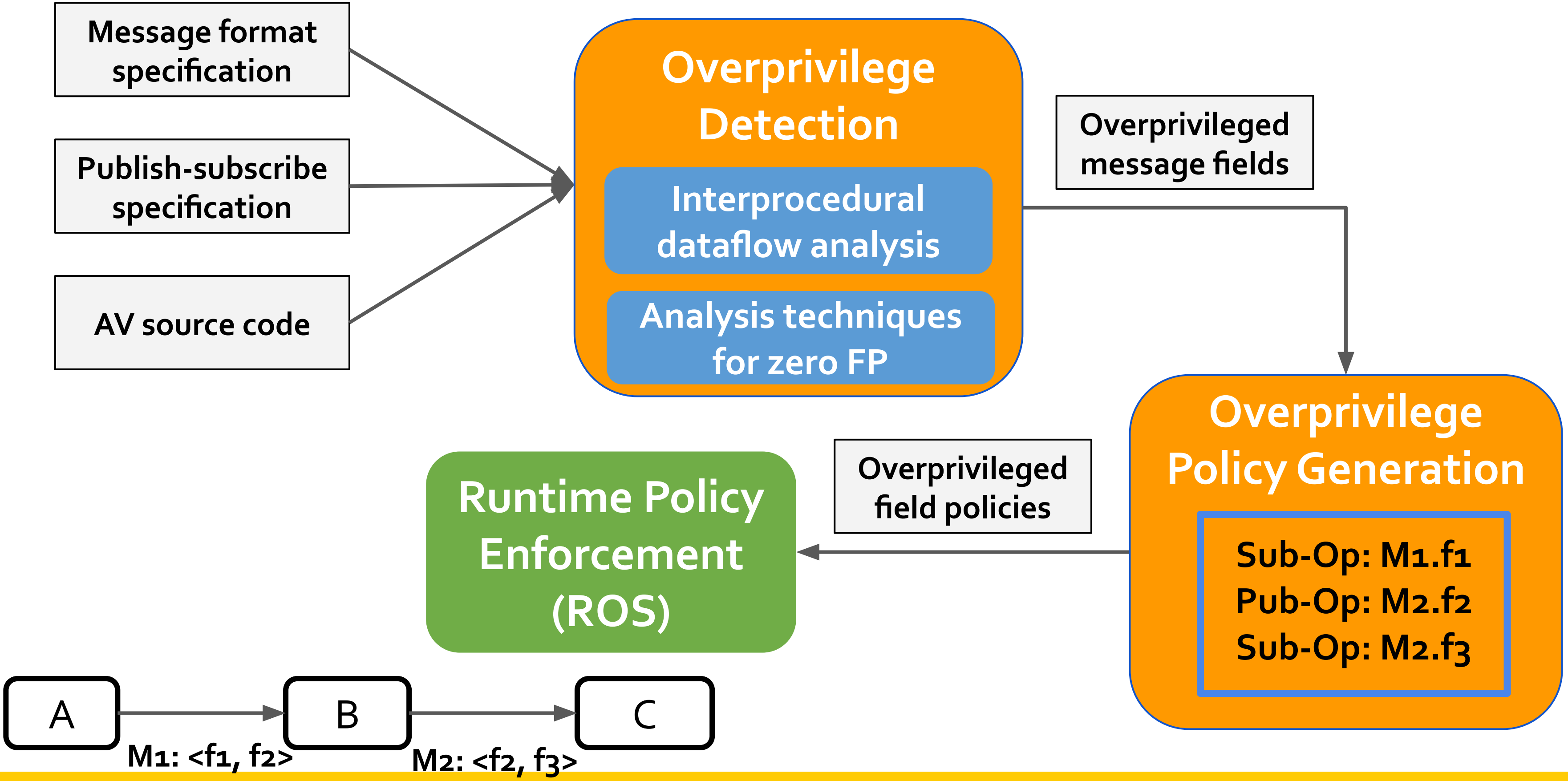

```
void TFBroadcaster::gps_to_transform_stamped(
    const ::apollo::localization::Gps& gps,
    geometry_msgs::TransformStamped* transform) {
    ……
    transform->header.stamp = time.fromSec(gps.header().timestamp_sec());
    ……
    transform->transform.translation.x = gps.localization().position().x();
    transform->transform.translation.y = gps.localization().position().y();
    transform->transform.translation.z = gps.localization().position().z();
    transform->transform.rotation.x = gps.localization().orientation().qx();
    transform->transform.rotation.y = gps.localization().orientation().qy();
    transform->transform.rotation.z = gps.localization().orientation().qz();
    transform->transform.rotation.w = gps.localization().orientation().qw();
}
```

Publisher-side overprivilege on *tf.transform*

Contribution

- Static program analysis ***incorporating AV-specific software programming models*** can lead to
  - Systematic discovery of security vulnerabilities and generation of access control defense policies in AV software systems
    - Built a publish-subscribe overprivilege detection and mitigation system, ***AVGuardian***, for ROS-based AV systems
    - Achieved zero false positive in overprivilege detection

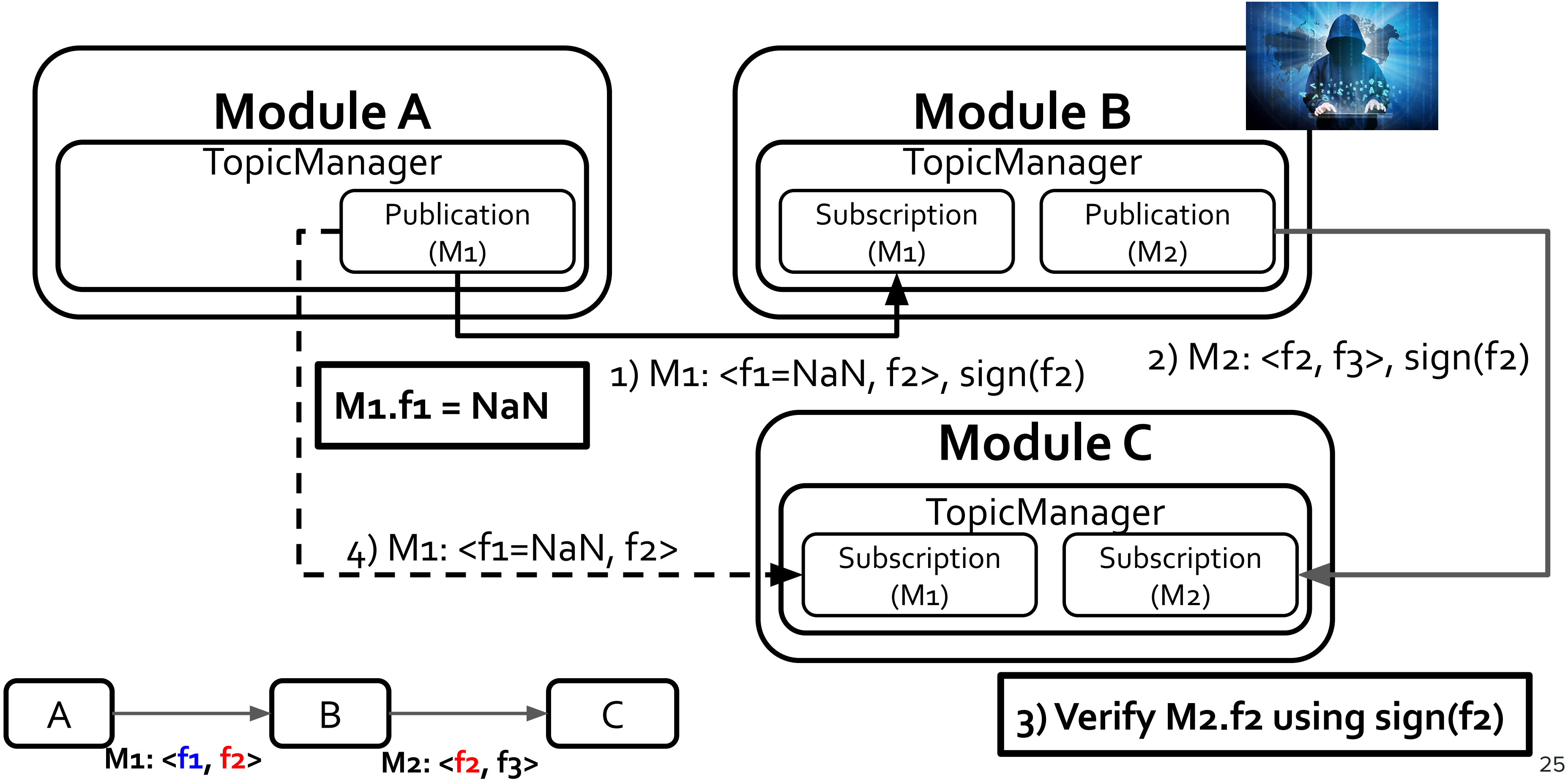
AVGuardian overview



Towards zero FP in overprivilege detection

- Challenges with static program analysis
  - **Virtual functions**
  - **Asynchronous event callbacks**
- Customized data flow analysis
  - Conservative subclass binding for virtual functions
  - Enumerating all possible orders of event callbacks
  - Reduced 28 false positives out of 523 true positives

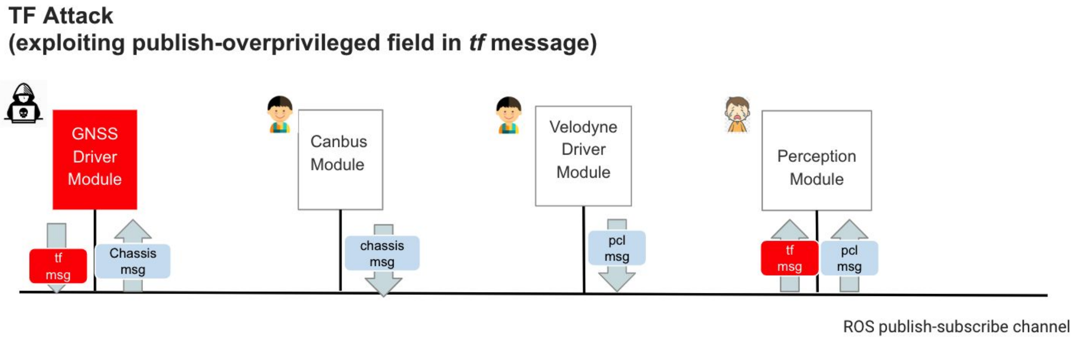
Defense: ROS-layer policy enforcement

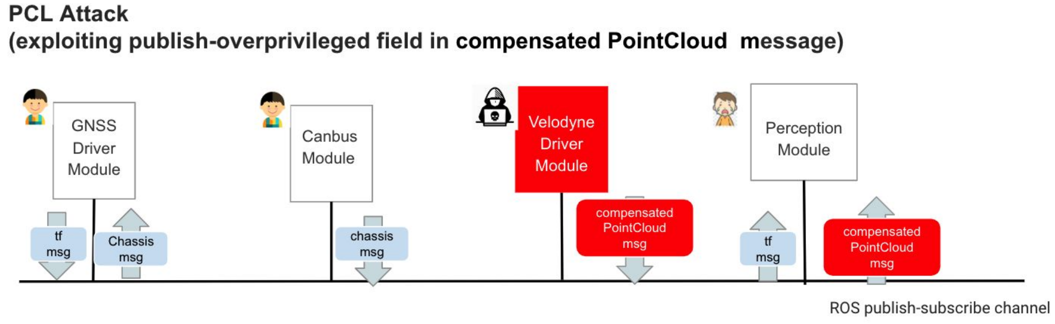


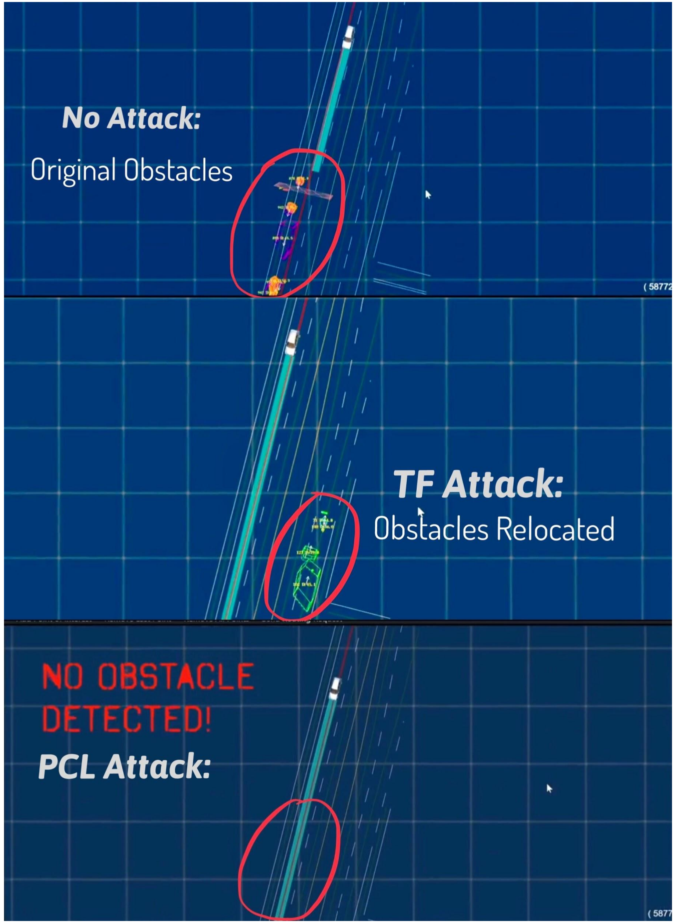
Vulnerability findings

- Exploits from publisher-side overprivilege
  - **TF attack** => obstacle relocation
  - **PCL attack** => obstacle remove
  - Security consequence: vehicle collision
- Exploit from subscriber-side overprivilege
  - **VIN stealing attack** => leakage of AV's VIN
  - Security consequence: AV owner's identity theft

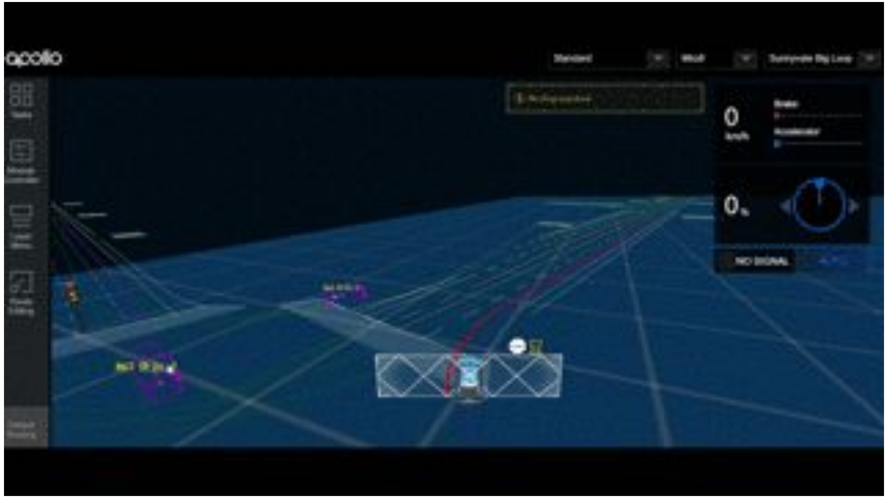
TF/PCL attack

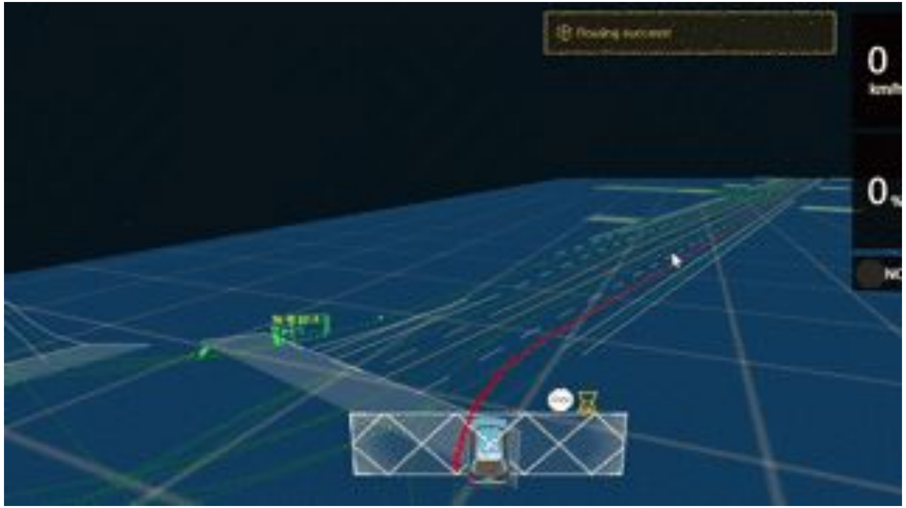






TF Attack: obstacle relocation

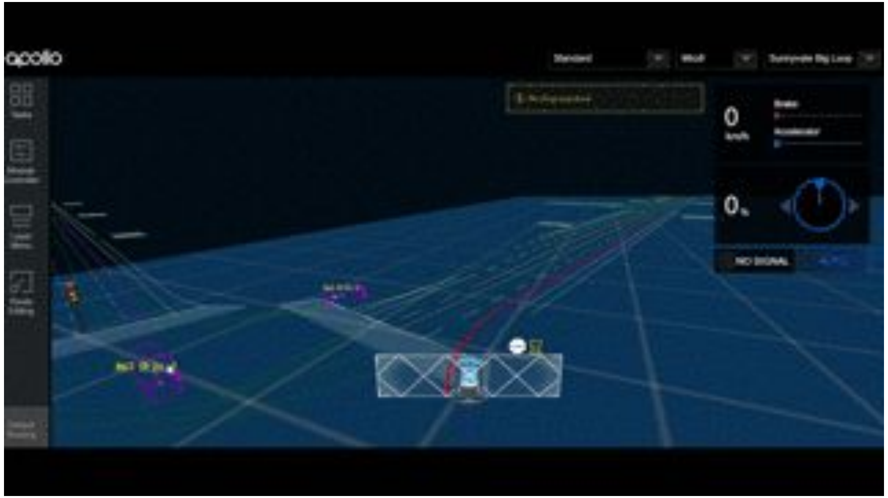




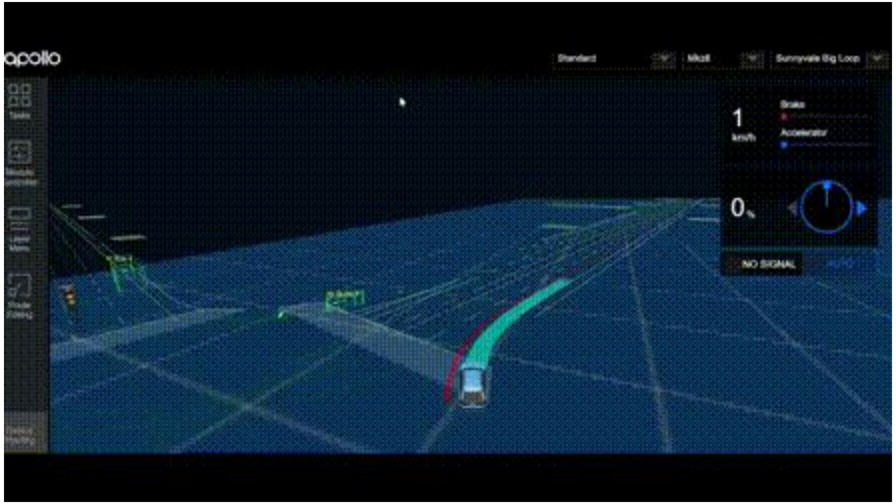
Control group video demo

TF attack video demo

PCL Attack: obstacle remove



Control group video demo



PCL attack video demo

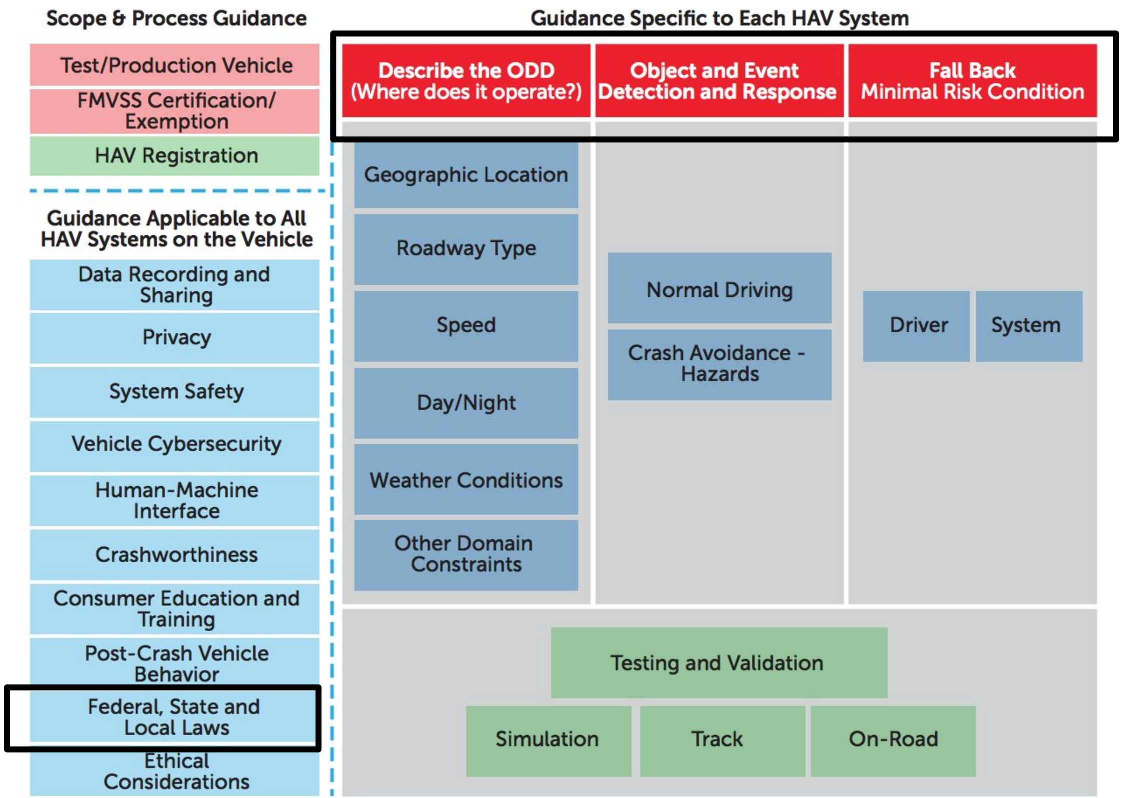
Conclusion (Part II)

- ***The first to design a static analysis framework*** for detecting and mitigating overprivilege in AV software systems
- Performed responsible disclosure to Baidu Apollo team and confirmed 3 attacks as valid

Part III: Verifying Self-Driving Safety Requirement Compliance for Autonomous Vehicle Systems

- A first driving safety verification framework for AV software
- Static analysis tool for systematic verification of safety rules

Safety requirements for AV software



Does AV software comply with the defined **object design domain (ODD)**, **object and event detection and response (OEDR)**, **minimal risk condition (MRC)**?

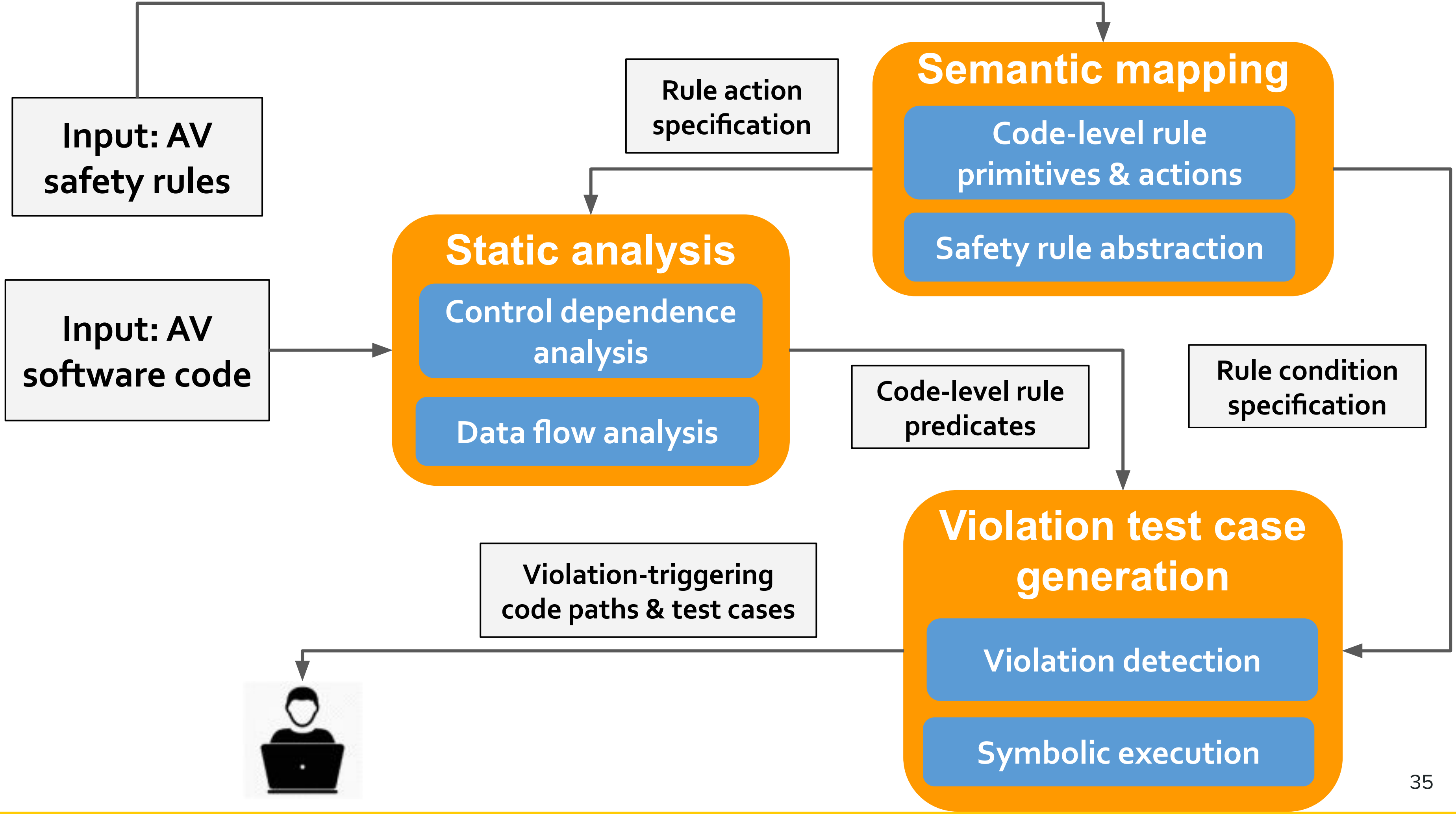
Does AV software generate self-driving decisions obeying **traffic law**?

Contribution

- Static program analysis ***incorporating self-driving semantics*** can lead to
  - Systematic detection of safety policy violation in the implementation of AV software
    - Built a safety compliance verification framework, ***AVerfier***, for AV software systems
    - Towards detecting policy violation with *zero false negative and low false positive*

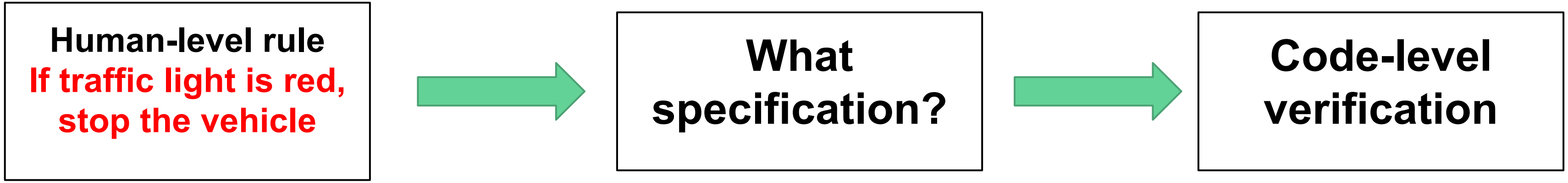
Related work & novelty

- Existing work in consistency checking of policy enforcement
  - Linux security policy & Android permissions
- Key difference: targeting at driving safety policies
  - Containing rich road traffic and driving semantics
  - Requiring specific formulation of driving safety policies to bridge the semantic gap between policy & code


Input: AV safety rules
Rule action specification
Semantic mapping
Code-level rule primitives & actions
Safety rule abstraction
Static analysis
Control dependence analysis
Data flow analysis
Input: AV software code
Code-level rule predicates
Rule condition specification
Violation test case generation
Violation detection
Symbolic execution
Violation-triggering code paths & test cases

Domain-specific challenge

- Definition of policy specification



- Solution
    - Policy specification composed by relevant APIs of the AV software

Safety policy specification example

- High-level policy
  - If ***traffic light is red***, ***stop*** the vehicle
- Specification
  - If ***signal.color() == TrafficLight::RED***, call ***BuildStopDecision***
- Validated generality on 35 safety rules of traffic laws

Towards completeness of rule verification

- Code-level rule predicate extraction
  - **Formulated as control dependencies**

A statement S2 is control dependent on S1 f and only if S2's execution is conditionally guarded by S1.

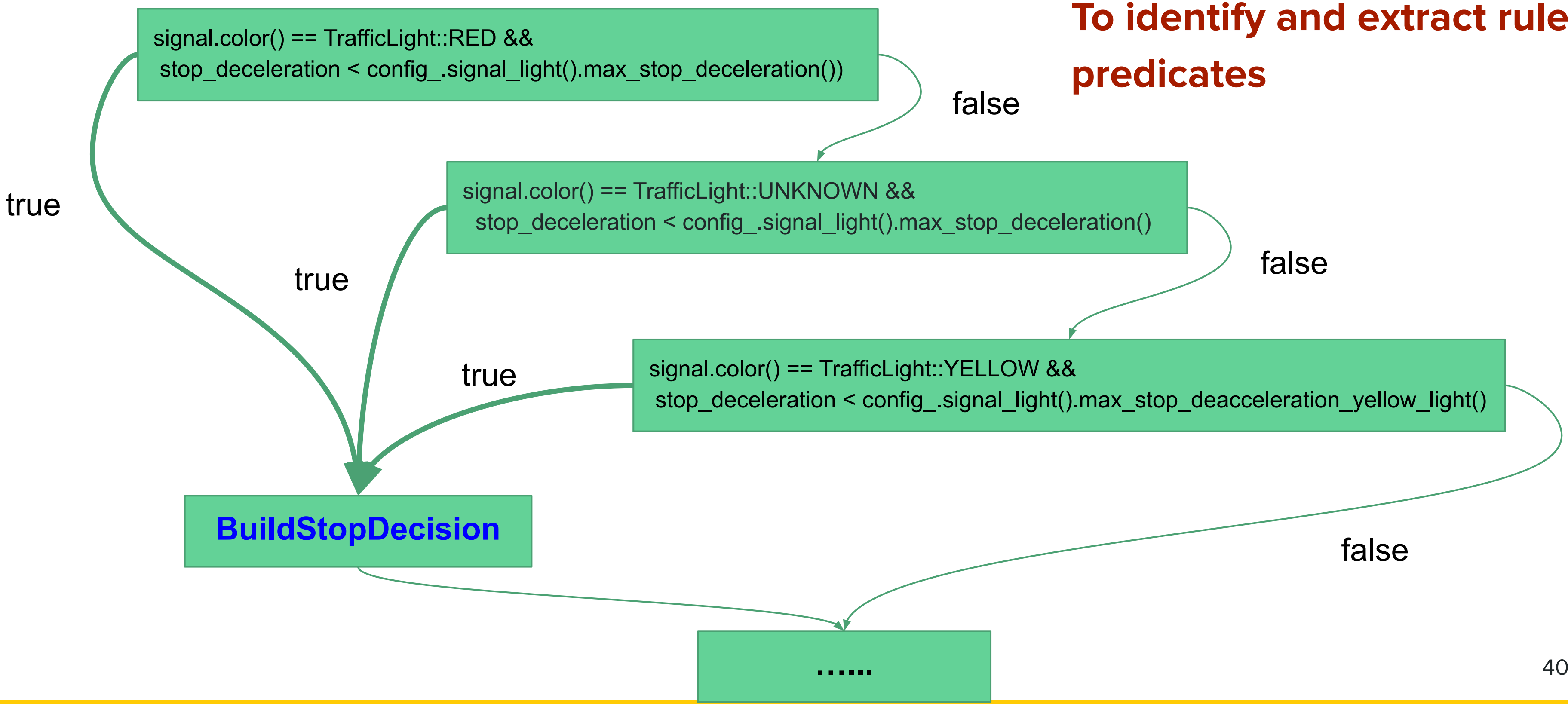
```
S1   if x > 2 goto L1
S2        y := 3
S3   L1: z := y + 1
```

Signal light case in Baidu Apollo

<table>
<tr><td>Action</td><td>SignalLight::ApplyRule</td></tr>
<tr><td>stop</td><td><pre>for (auto& signal_light : signal_lights_from_path_) {
      ……
      if ((signal.color() == TrafficLight::RED &&
         stop_deceleration < config_.signal_light().max_stop_deceleration()) ||
         (signal.color() == TrafficLight::UNKNOWN &&
         stop_deceleration < config_.signal_light().max_stop_deceleration()) ||
         (signal.color() == TrafficLight::YELLOW &&
         stop_deceleration < config_.signal_light().max_stop_deacceleration_yellow_light())) {
           ……
         if (BuildStopDecision(frame, reference_line_info, &signal_light)) {
           has_stop = true;
           signal_debug->set_is_stop_wall_created(true);
         }
       }
       ……
 }</pre></td></tr>
</table>

Control dependency analysis

To identify and extract rule predicates



Towards completeness of violation checking

```
  ......
  if (stop)
    pedestrians.push_back(obstacle_id);
}
if (!pedestrians.empty()) {
  // stop decision
  double stop_deceleration = util::GetADCStopDeceleration(reference_line_info, crosswalk_overlap->start_s,
      config_.crosswalk().min_pass_s_distance());
  if (stop_deceleration < config_.crosswalk().max_stop_deceleration())
      crosswalks_to_stop.push_back(std::make_pair(crosswalk_overlap, pedestrians));
}
}
for (auto crosswalk_to_stop : crosswalks_to_stop)
  BuildStopDecision(frame, reference_line_info, const_cast<hdmap::PathOverlap*>(crosswalk_to_stop.first),
                    crosswalk_to_stop.second);
```

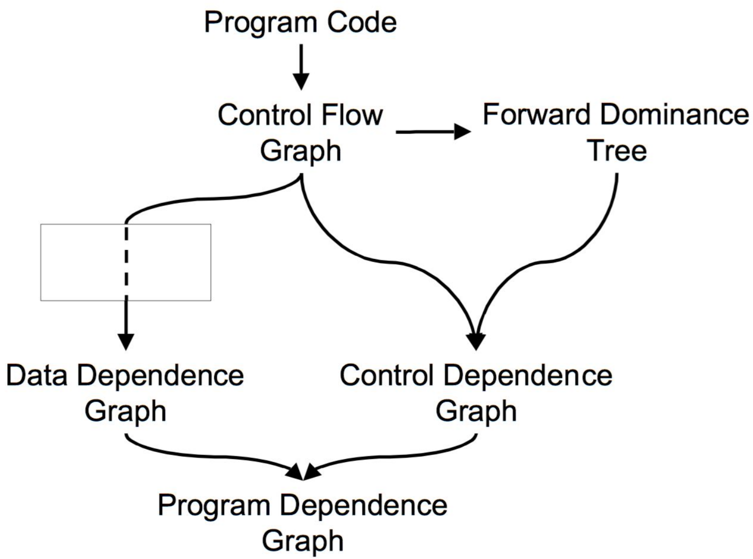
Implicit dependency (only if *pedestrians* is not empty)

Implicit dependency (only if *crosswalks_to_stop* is not empty)

Only one control-dependent predicate identified

Towards completeness of rule verification

- Code-level rule predicate extraction
  - **Program dependence analysis**



Policy inconsistency findings in Apollo

- Rule 1: Slow down to 15 mph when approaching a speed bump.
  - Found in Apollo v3.0 fixed in Apollo v3.5
- Rule 2: Do not pass if you are within 100 feet of an intersection.
  - Found in Apollo v3.0 fixed in Apollo v3.5

Towards low FP rate of violation detection

- Given a violation detected in policy checking, apply ***symbolic execution*** to systematically validate that a true violation exists
    - Symbolic execution gives proof of completeness
    - Engineering challenge with extending KLEE to run on AV software code base

Future research directions

- Systematic test case generation for violation
  - Preprocessing through flow analysis to prune irrelevant control flow paths
  - Only apply symbolic execution on relevant paths
- Semantic comparison
  - How to compare code-level predicates with specification
    - Inclusive, partial overlapping, etc.

Conclusion (Part III)

- ***The first to design a static analysis framework*** for driving safety compliance verification in AV software systems
- Proposed AV semantic mapping to enable flexible specification of driving safety policies with AV software code-level semantics

Conclusion

Performance, ***security*** and ***safety*** are key requirements for smart end systems.

We perform ***system-specific customization*** on systematic software analysis approaches for effective ***requirement testing and verification*** of smart system software.

Acknowledgement

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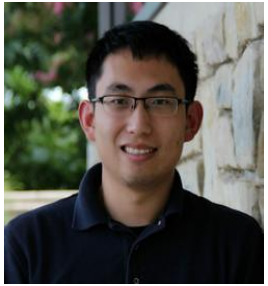

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Conclusion

Performance, security and safety are key requirements for smart end systems

We incorporate system-specific knowledge to customize systematic software analysis approaches for effective requirement testing and verification of smart system software

Reference

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