Detecting Missing-Check Bugs via Semantic- and Context-Aware Criticalness and Constraints Inferences

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Contributions

- Missing-check bug detection for OS kernels
  - Scalable and context-aware interprocedural static analysis techniques
- Identification of critical variables, peers, and indirect-call targets (additional 93% reduction)
- 278 new bugs in Linux 4.20
  - 151 patches confirmed with 134 in mainline

Security checks safeguard the OS kernel state

- Kernels are critical, complex, and error prone
- Developers enforce numerous (>400k) security checks
- What is a security check? [LRSan CCS’18]
    - Conditional statements (e.g., *if* statement) with at least two branches
        - At least one branch has error handling **and**
        - At least one branch does NOT have error handling

Not a security check if all branches have or do not have error handling

Common classes of security checks

```
/* Input validation */
res = get_user(size, buf);
if (size > MAX)
    return -EINVAL;
```

```
/* Check operation result */
*vaddr = pic_alloc(...);
if (*vaddr == NULL)
    return -ENOMEM;
```

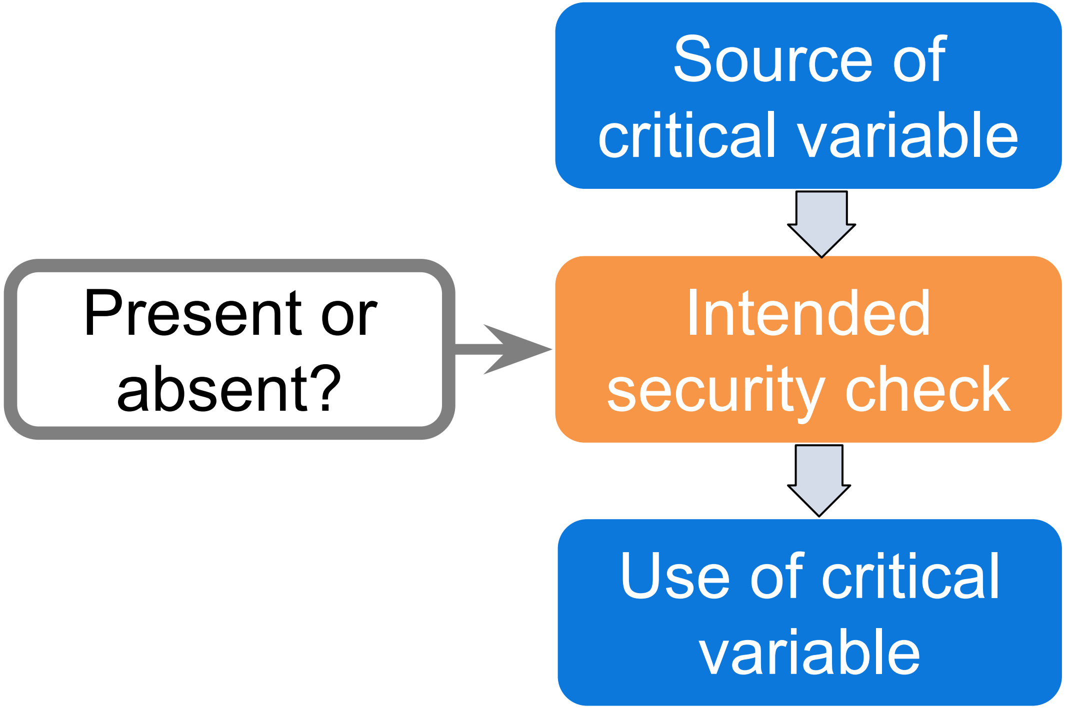
```
/*Missing permission check*/
if (!access_ok(VERIFY_WRITE, addr, size))
    return -EFAULT;
```

```
/*Check system state */
if (!PGE_EMPTY(agp_bridge))
    return -EBUSY;
```

Who guards the guardians ?

- Security checks themselves are buggy
- The most common case is - a security check itself is missing

Missing-check bugs: Not enforcing a required security check on critical variable



Source of critical variable

Intended security check

Use of critical variable

Present or absent?

Importance of detecting missing-check bugs

- Adding/updating checks constitute 59.5% of vulnerability patches
- Security impacts of missing-check
    - Denial of Service
    - Memory Corruption
    - Information leakage
    - ...

Possible detection approaches and challenges

- Rule-based approach to identify these bugs
    - Challenges
        - Require semantic understanding
        - Hard to generalize
- Cross-checking (i.e., statistical analysis)
    - Our choice

The idea of cross-checking

- Statistical model that avoids computing ground truth
  - Majority decision is applied to the group
  - Minority cases are likely bugs
  - Assumption: majority kernel code is good
- 9 out of 10 doors use deadbolts for security
  - A door without deadbolt is likely unsecure

Challenges in cross-checking

- Scalability: Can’t cross check every variable
    - Focus on critical variables only
- Similarity: Generate statistically significant peers
    - Find sufficient semantically-similar code
- Granularity: Optimize the comparison levels
    - Not too coarse-grained or too fine-grained

High-level overview of Crix

- Crix - Criticalness and constraints Inferences for detecting missing checks

Identify critical variables → Find peers → Model checks → Detect deviations as bugs

Critical variable identification solves scalability

Insights (1) a variable is critical if it is validated in a security check; (2) Checked variables can propagate criticalness

- Collect checked variables as initial seed
- Collect sources and propagated variables of each critical variable

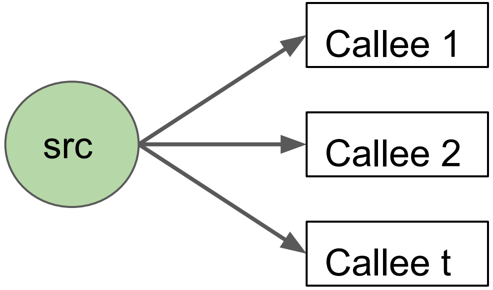
```
//Allocate a netlink msg
skb = genlmsg_new(...);
//Allocation success check
if (!skb)
  return -ENOMEM;
//skb criticality propagated
nla_put(skb,...);
```

Automatically Identifying Security Checks for Detecting Kernel Semantic Bugs, Lu et.al, ESORICS 2019, Part II, LNCS 11736

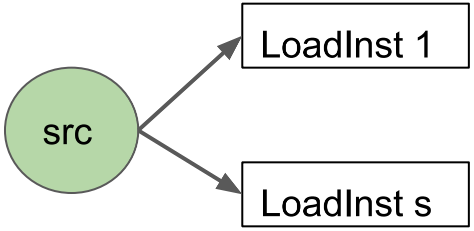
Tackling similarity by identifying peers in kernels

- **Requirement:** A large set; similar context & semantics
- **Observation:** indirect calls, return inst, direct callers generate peers
- **Approach:** Slice from critical variable to src & use

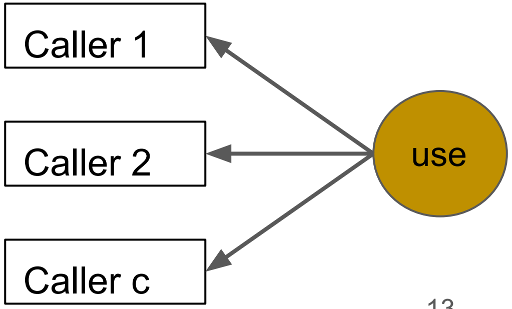
Indirect call (Arg)



Return Inst (rval)



Direct call (parm)



Precisely identifying indirect call targets

- Challenge: scalability, callgraph precision
- Indirect calls peers share similar arguments
  - Count & type
- Currently, indirect call targets are identified via
  - Points-to analysis or Function-type matching
- Our new approach - Two-layer type analysis

Two-layer Type Analysis for accurate indirect call peers identification

- First layer - function type matching
    - *add(int a, int b)* vs *add1(int a, int b, int c)*
- Second layer - struct type matching
    - Function pointers are stored in a struct field **&**
    - Loaded from this struct field during dereference
- Uses escape analysis for soundness

Cross checking peers to detect deviations

- Use global threshold, Relative Frequency (RF = 0.15)

$$\boxed{RF = N_{nc} / N_t}$$

- RF: ratio of slices missing a check (N_{nc}) to total number of slices (N_t)
- RF determined via empirical study of security patches

Implementation of Crix

- Multiple LLVM 8.0 passes
- 4.5K lines C++ code
- 64 minutes to complete
- 17,343 modules for x86 *allyesconfig*
- Uses threshold (RF) to prioritize 804 bugs
    - Ranking as a heuristic

Evaluating Crix on Linux Kernel 4.20

- 278 new bugs
  - 134 applied to mainline
  - 99 bugs fixed within one week of submission
  - 195 bugs in driver modules
    - 27 driver modules have >1 bug
  - Latent period of 4 years 7 months
    - 10% have latent period over 10 years

Besides Alias Analysis, Crix has more limitations

- Context determination is not comprehensive
  - In error paths, missing checks are often considered unnecessary

https://www.nationalgeographic.org/media/sinking-of-the-titanic/

Conclusion

- Security checks are critical but buggy
- Finding, modeling, cross-checking peer slices for semantic- & context-aware detection
- 93% **more** reduction in indirect call targets compared to existing techniques
- Code @ https://github.com/umnsec/crix