Auto-detecting sleeping lock calls in non-preemptible context via static analysis

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Outline

The problem

Proof-of-concept tool

- Algorithm design
- Implementation
- Demo

Improving the approach

The problem

The problem

- real-time kernel (PREEMPT_RT) changes the semantics of spin locks into sleeping locks
- sleeping locks, unlike standard spin locks, cannot be used when preemption is disabled
- affects all subsystems and drivers
- leads to kernel panic when the locks actually sleeps (i.e. is taken)

Example

- detected when running BPF map selftests on RT kernel[1]

```
BUG: sleeping function called from invalid context at
kernel/locking/spinlock_rt.c:35
in_atomic(): 1, irqs_disabled(): 0, non_block: 0,
pid: 17709, name: test_sockmap
Preemption disabled at:
sock_map_update_elem_sys+0x8f/0x2a0
Call Trace:
dump_stack+0x5c/0x80
 ___might_sleep.cold.95+0xf5/0x109
rt_spin_lock+0x3d/0xd0
___slab_alloc+0xc8/0x8d0
kmem_cache_alloc_trace+0xe7/0x220
sock_hash_update_common+0x54/0x4d0
sock_map_update_elem_sys+0x25a/0x2a0
```

[1] https://lore.kernel.org/lkml/ZMOrEi3cNWGXp9ZS@krava/t/

Solution?

Manually fix each case when encountered

Solution? (2)

~~Manually fix each case when encountered~~

Alternative: **Automatic detection** of sleeping functions called from invalid context

Proof-of-concept tool

What pattern to look for?

- simplest case:

```
preempt_disable();
...
spin_lock(...);
...
```

- more general case:

```
f1(); // f1 calls preempt_disable()
...
f2(); // f2 calls spin_lock()
```

- both calls may be several levels down in the call stack

General case (1)

- second case from previous slide is as general as possible (if control flow is taken into account)
  - = there is a corresponding sequence of that form for all cases of sleeping function called from invalid context
- proof:
  - to trigger the bug, there must be a call of spin_lock() or another sleeping lock inside a function; we name it f
  - now, either there is a preceeding call to a function calling preempt_disable (we name it g) in f preceeding the call to spin_lock
  - or a function calling preempt_disable (again called g) is called before a call to f upper in the stack, in another function; we name it h

General case (2)

- first case:

```
f(...) { ...
    g();            // f1 from pattern
    ...
    spin_lock(...); // f2 from pattern
... }
```

- second case:

```
h(...) { ...
    g(...); // f1 from pattern
    ...
    f'(...); // f2 from pattern; calls f eventually
... }
```

- → it is enough to look for this pattern

Graph algorithm

- to detect the pattern in a function (without any control statements), one needs to do two things:
    - know how its callees behave regarding scheduling and preemption (this we call *preemption* and *scheduling semantics*)
    - whether a callee that calls schedule() is present at a place in the function where preemption is disabled
- this can be easily done by recursion on a function call graph
    - assigning semantics to functions done at the same time as finding violations
    - if semantics are unknown for a callee, the assignment procedure is called recursively on it
    - requires having a set of functions with pre-assigned semantics

Graph algorithm example (1)

example of the graph algorithm (modeled roughly on the bpf sockmap BUG):

```
int map_lock() {
    preempt_disable();
}

int map_unlock() {
    preempt_enable();
}

int access_map() {
    map_lock();
    spin_lock(&another_lock);
    _access_map();
    spin_unlock(&another_lock);
    map_unlock();
}
```

```
known semantics:
    preempt_disable:
        disables preemption
    preempt_enable:
        enables preemption
    spin_lock:
        sleeps
```

Graph algorithm example (2)

example of the graph algorithm (modeled roughly on the bpf sockmap BUG):

```
int map_lock() {
    preempt_disable();
}

int map_unlock() {
    preempt_enable();
}

int access_map() {
    map_lock();
    spin_lock(&another_lock);
    _access_map();
    spin_unlock(&another_lock);
    map_unlock();
}
```

```
known semantics:
    preempt_disable:
        disables preemption
    preempt_enable:
        enables preemption
    spin_lock:
        sleeps
    access_map:
       no change
```

Graph algorithm example (3)

example of the graph algorithm (modeled roughly on the bpf sockmap BUG):

```
int map_lock() {
    preempt_disable();
}

int map_unlock() {
    preempt_enable();
}
int access_map() {
    map_lock();
    spin_lock(&another_lock);
    _access_map();
    spin_unlock(&another_lock);
    map_unlock();
}
```

```
known semantics:
    preempt_disable:
        disables preemption
    preempt_enable:
        enables preemption
    spin_lock:
        sleeps
    access_map:
      no change
```

Graph algorithm example (4)

example of the graph algorithm (modeled roughly on the bpf sockmap BUG):

```
int map_lock() {
    preempt_disable();
}

int map_unlock() {
    preempt_enable();
}

int access_map() {
    map_lock();
    spin_lock(&another_lock);
    _access_map();
    spin_unlock(&another_lock);
    map_unlock();
}
```

```
known semantics:
    preempt_disable:
        disables preemption
    preempt_enable:
        enables preemption
    spin_lock:
        sleeps
    access_map:
        no change
    map_lock:
        no change
```

Graph algorithm example (5)

example of the graph algorithm (modeled roughly on the bpf sockmap BUG):

```
int map_lock() {
    preempt_disable();
}

int map_unlock() {
    preempt_enable();
}

int access_map() {
    map_lock();
    spin_lock(&another_lock);
    _access_map();
    spin_unlock(&another_lock);
    map_unlock();
}
```

```
known semantics:
    preempt_disable:
        disables preemption
    preempt_enable:
        enables preemption
    spin_lock:
        sleeps
    access_map:
        no change
    map_lock:
        disables preemption
```

Graph algorithm example (6)

example of the graph algorithm (modeled roughly on the bpf sockmap BUG):

```
int map_lock() {
    preempt_disable();
}

int map_unlock() {
    preempt_enable();
}

int access_map() {
    map_lock();
    spin_lock(&another_lock);
    _access_map();
    spin_unlock(&another_lock);
    map_unlock();
}
```

```
known semantics:
    preempt_disable:
        disables preemption
    preempt_enable:
        enables preemption
    spin_lock:
        sleeps
    access_map:
        disables preemption
    map_lock:
        disables preemption
```


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Graph algorithm example (7)

example of the graph algorithm (modeled roughly on the bpf sockmap BUG):

```
int map_lock() {
    preempt_disable();
}

int map_unlock() {
    preempt_enable();
}

int access_map() {
    map_lock();
    spin_lock(&another_lock);
    _access_map();
    spin_unlock(&another_lock);
    map_unlock();
}
```

```
known semantics:
    preempt_disable:
        disables preemption
    preempt_enable:
        enables preemption
    spin_lock:
        sleeps
    access_map:
        disables preemption, sleeps
    map_lock:
        disables preemption
```

Graph algorithm example (8)

Violation detected!

Graph algorithm example (9)

Output from PoC tool (more about it on next slide):

```
$ bin/rtlockscope /tmp/artificial_case/ kb/default-rt.yaml
...
Sleeping lock called at:
access_map at case.c:9
spin_lock at case.c:11

preemption disabled at:
access_map at case.c:9
map_lock at case.c:10
preempt_disable at case.c:2

Statistics:
- 1 cases found
```

rtlockscope tool[2]

- prototype tool for auto-detecting scheduling with preemption disabled
- accepts two arguments: the source code tree and a *knowledge base*
  - the KB is in YAML format and represents the initial knowledge about semantics
- makes use of graph algorithm described above (plus call stack backtracking, as seen on previous slide)
- currently quite simple (under 400 lines of Python code), makes use of external tools
  - `ctags` is used to find all functions in a source tree
  - `cscope` is used to look up callees of functions

[2] `https://gitlab.com/tglozar/rtlockscope`

rtlockscope knowledge base

```
$ cat kb/default-rt.yaml
# Direct preemption setting functions
preempt_disable:
  preempt-semantics: preempt-disabling
preempt_enable:
  preempt-semantics: preempt-enabling
...
# Sleeping locks
schedule:
  lock-semantics: sleeping
spin_lock:
  lock-semantics: sleeping
```


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The important question (1)

Does rtlockscope work *reasonably well* on the Linux kernel?

The important question (2)

Does rtlockscope work *reasonably well* on the Linux kernel?

Kind of.

rtlockscope false positive example

```
if (a)
    preempt_disable();
if (!a)
    schedule();
if (a)
    preempt_enable();
```

rtlockscope false negative example

```
preempt_enable();
while (...) {
    schedule();
    preempt_enable();
    ...
    preempt_disable();
}
```

Current rtlockscope limitations

- rtlockscope ignores the *control flow* of the program
- the sequence of function calls ordered by the source code is not necessarily the one occuring at runtime
- e.g. loops, conditional statements, recursion
- usually, this is not a problem, since the enabling and disabling of preemption usually wraps a block of code
- an issue is that one wrongly assigned semantics can generate or suppress thousands of violations

Simple workaround

- = add functions which are labeled wrong to KB with correct labeling
- requires manual updates to the KB, but keeps the algorithm simple
- theoretically sound and complete (in worst case, label all functions)

Demo

rtlockscope run on a Linux kernel source tree (6.10.3)[3]

[3] asciinema, result.log

Improving the approach

How to improve rtlockscope further?

- one way is to keep refining the knowledge base (adding new annotations for problematic functions)
- another one is to improve the algorithm
- idea: view the problem as finding and checking possible sequences of events
- this separates it into two parts:
  - find the set of all possible sequences of relevant events ("traces")
  - determine from the set if a violation can happen
- this turns out to be a useful way of viewing the problem

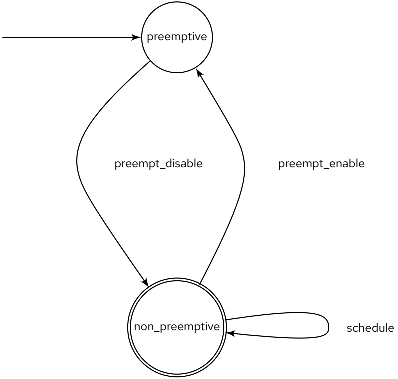
Formal representation of the problem

- let $E = \{PE, PD, S\}$ be a set of events we are interested in
  - PE ... `preempt_enable`
  - PD ... `preempt_disable`
  - S ... `schedule`
- let $A \subseteq E^*$ be the set of all sequences of events that can happen on a system
- let $V \subseteq E^*$ be the set of all violations, i.e. sequences where `schedule` is called under non-preemptible context
- statement of problem: prove $A \cap V = \emptyset$

Properties of sequence sets *A*, *V*

- *V* is either a regular language or context-free language, depending on whether nesting is allowed
- thus, it is representable with a finite-state automaton or a push-down automaton
- automaton representation is used, for example, in kernel rv subsystem[1] for runtime verification
- *A* is more complicated, since it derives from the program itself (the Linux kernel)
    - in rv, one concrete sequence of events is observed on a live kernel
    - here in static analysis, we have to account for all such possible sequences

rtlockscope problem as an automaton



rtlockscope as event sequence generator

- instead of determining semantics, attach a set of event sequences to each function to the kernel
- then check each sequence for violations
- practically, this is the same as the original graph algorithm: the semantics assigned by rtlockscope are just a function between states of the automaton given by the corresponding sequences
- however, this point of view gives us intermediate representation that can be processed further

Sequence assignment example

same program as seen before, but with assigned sequences (as regexes) instead of semantics

```
int map_lock() {
    preempt_disable();
}

int map_unlock() {
    preempt_enable();
}

int access_map() {
    map_lock();
    spin_lock(&another_lock);
    _access_map();
    spin_unlock(&another_lock);
    map_unlock();
}
```

```
event sequences:
    preempt_disable:
        PD
    preempt_enable:
        PE
    spin_lock:
        S
    map_lock:
        [preempt_disable] = PD
    map_unlock:
        [preempt_enable] = PE
    access_map:
        [map_lock] [spin_lock] [map_unlock]
         = PD S PE
```

Advantages of sequence representation

- sequences closely resemble the original source code but drop all details unnecessary for the analysis
- regular expressions can be used to represent sequence sets
- sequence representation can be extended to include control sequences:

```
if (a) PD
if (!a) S
if (a) PE
```

- the extended representation can be seen and manipulated as superset of C, and transformations may be applied to common patterns in code[4]

[4] For another static analysis project using patterns on the Linux kernel, see DiffKemp[2]

Sequence transformation pattern example

```
if (EXPR)
    PD;
if (!EXPR)
    S;          ---->  (PD PE) + (S)
if (EXPR)
    PE;
```

Some challenges

- implementing patterns efficiently without blow-up of the number of event sequences
- creating a database of patterns that is efficient on the Linux kernel in addition to a knowledge base

Conclusion

- static analysis can be used to detect at least some scheduling while atomic issues in the Linux kernel
- although static analysis is theoretically hard, real-world programs have only a limited degree of complexity that can be resolved with specialized algorithms
- the rtlockscope approach is connected to the kernel’s rv subsystem and the formalism under it as well as the approach of DiffKemp
- possible generalization to other verification problems

Questions?

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  In Mohammed-Amine Koulali and Mira Mezini, editors, Networked Systems, pages 265–282, Cham, 2022. Springer International Publishing.