Automatically Proving Microkernel Security

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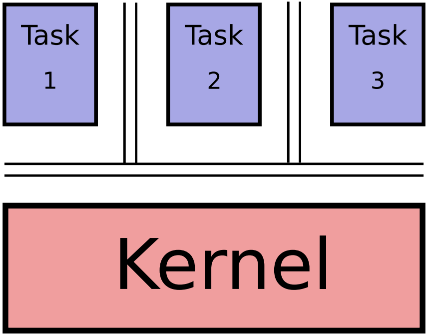
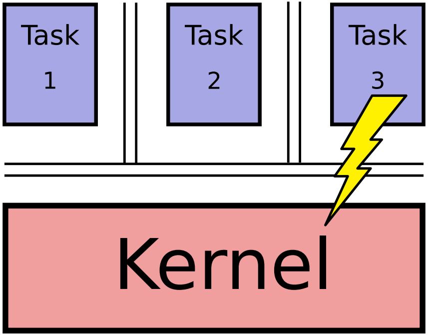


Kernels are critical to security.



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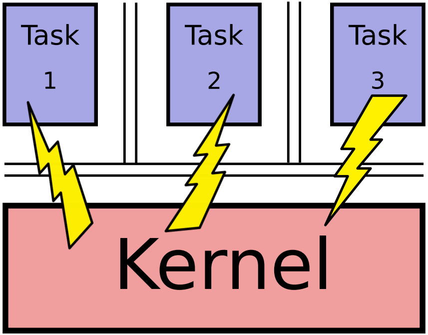

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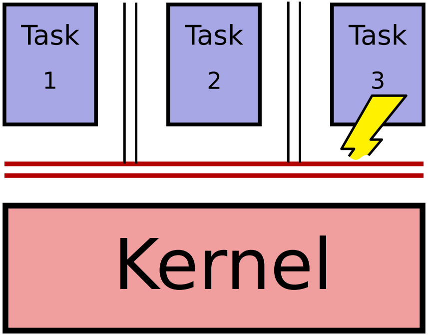

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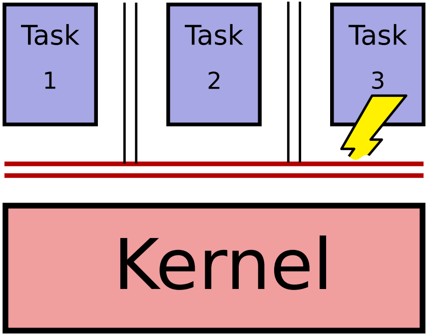


Kernels are critical to security.

Our goal:

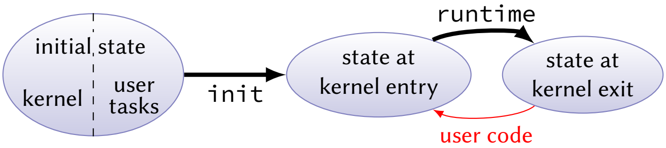
- prove absence of privilege escalation (APE).
- prove absence of run-time errors (ARTE).

Automatically, with few annotations, from the machine code

Scope

We focus on embedded kernels.

- No dynamic allocation



Protection mechanisms

- page tables, or
- segments (32-bit x86)

Specify (address range, permissions) pairs.
To verify: at kernel exit, the memory protection state is correct.
Requires analyzing all the kernel's code.

Challenge 1: machine code analysis

```c
void hw_context_idle(void) {
  struct context *high = context_idle();
  struct hw_context *ctx = &high->hw_context;

  asm volatile
    ("mov %0,%%esp" : : "r"((uintptr_t) ctx + sizeof(struct pusha)
                          + sizeof(struct intra_privilege_interrupt_frame))
                    : "memory");
  asm("sti");
  asm("hlt");
  asm("jmp error_infinite_loop");
  __builtin_unreachable ();
}
```

Challenge 1: machine code analysis

- no control flow
- no types, no memory partitioning
- masks, legitimate overflows, low-level comparisons, etc.

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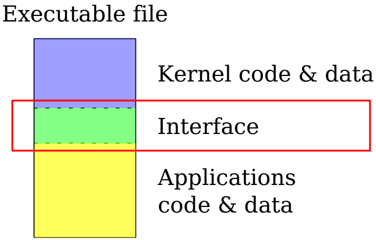
Contribution

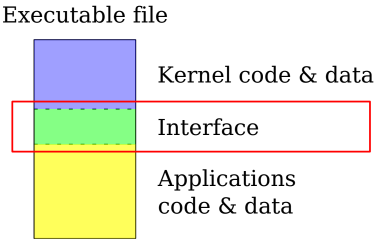
BINSEC/CODEX, a static analyzer based on **abstract interpretation**.

- Computes CFG on-the-fly
- Rich numerical abstractions + symbolic information

Challenge 2: parameterized kernels



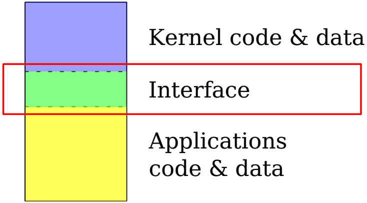
Challenge 2: parameterized kernels




```
type Flags = Int8 with (self & PRIVILEGED) == 0;
type Context = struct { Int8 pc; Int8 sp; Flags flags; };

type Segment = struct {
  Int8 base;
  Int8 size_and_rights;
} with self.base ≥ kernel_last_addr

type Memory_Table = struct { Segment code; Segment data; }

type Thread = struct {
  Memory_Table ∗mt;
  Context ctx;
  Thread ∗next; }

type Interface = struct {
    Thread[nb_thread]∗ threads;
    (Int8 with self = nb_threads) threads_length; }
```

Challenge 2: parameterized kernels

Executable file



Contribution

A type-based memory analysis

```
type Flags = Int8 with (self & PRIVILEGED) == 0;
type Context = struct { Int8 pc; Int8 sp; Flags flags; };

type Segment = struct {
  Int8 base;
  Int8 size_and_rights;
} with self.base ≥ kernel_last_addr

type Memory_Table = struct { Segment code; Segment data; }

type Thread = struct {
  Memory_Table *mt;
  Context ctx;
  Thread *next; }

type Interface = struct {
   Thread[nb_thread]* threads;
   (Int8 with self = nb_threads) threads_length; }
```

Experimental evaluation

Case study 1: EducRTOS

- Small academic OS developed for teaching purposes
- Both separation kernel and real-time OS, dynamic thread creation
- 1,200 x86 instructions.
- Protection by segmentation.

Proved APE and ARTE on 96 variants of EducRTOS. Varying parameters:

- compiler (GCC/Clang), optimization flags
- scheduling algorithm, dynamic thread creation (enabled/disabled)...

Verification time: from 1.6 s to 73 s.
14 lines of annotations.

Experimental evaluation

Case study 2: AnonymOS

- Industrial microkernel used in industrial settings
- Multicore
- 329 functions, ~10,000 instructions
- Protection using page tables.

2 versions

- BETA version: 1 vulnerability
- v1 version: vulnerability fixed

Specific = *Generic* + restriction on stack sizes

		Generic annotations		*Specific* annotations	
# shape annotations	generated	1057			
	manual	57 (5.11%)		58 (5.20%)	
Kernel version		BETA	v1	BETA	v1
invariant computation	status	✓	✓	✓	✓
	time (s)	647	417	599	406
# alarms in runtime		1 **true error** 2 false alarms	1 false alarm	1 **true error** 1 false alarm	**0** ✓
user tasks checking	status	✓	✓	✓	✓
	time (s)	32	29	31	30
Proves APE?		N/A	∼	N/A	✓

Proved APE and ARTE in 430 s.
58 lines of annotations.

Summary and perspectives

- Verification of APE and ARTE on kernels is possible
- from the binary
- unbounded loops
- small number of manual annotations.

Submission under review: O. Nicole, M. Lemerre, S. Bardin, X. Rival, “No Crash, No Exploit: Automated Verification of Embedded Kernels”, *arXiv:2011.15065*

Perspectives

- Non-interference between tasks
- Analysis of other software
- Efficient verification of memory safety (70 % of vulnerabilities[1])
- Mixed-language analysis, off-the-shelf component analysis

[1] M. Miller, Trends, challenges, and strategic shifts in the software vulnerability mitigation landscape, *BlueHat IL*, 2016