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improvements

Kernel security hacking for the Internet of Things

IoT

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Kernel security hacking for the IoT

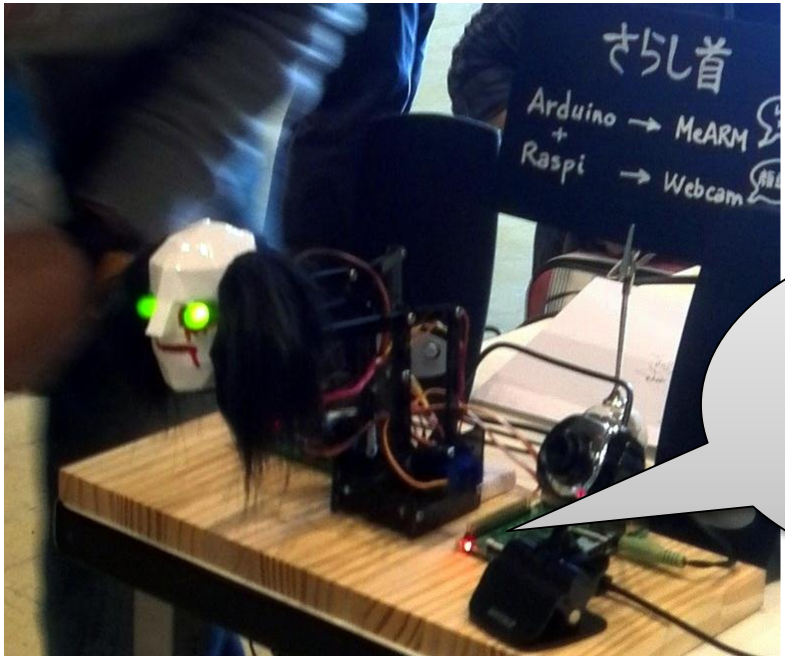
1. **Introduction**
2. **Reducing the attack surface**
3. **Leveraging determinism**
4. **Protecting the critical software**
5. **Conclusions**

About me

- **Real-time embedded systems engineer**
  - Started with real-time embedded software and drivers (8 years).
    - MaRTE OS (Ada95 RTOS), SafeG (ARM Trustzone monitor), TOPPERS/FMP (Japanese multi-core RTOS).
  - Now, mostly customizing Linux for embedded devices (2 years).
    - Yocto-based project: META-DEBIAN (talk on Friday 5th, 16:20h)
    - Long-term Support Industrial (LTSI) kernels + Real-time patch
- **Not a security expert**
  - Trying to catch up with such a broad subject.
- **Hobbies**
  - Manga, Puramoderu, hiking, futsal, …

Purpose of this talk

- **Two main purposes**
  - Raise concern about the security of embedded systems in the IoT.
  - Share a few things I learned while investigating Linux security and encourage you to try and share your own techniques.
    - https://github.com/sangorrin/linuxcon-japan-2015



Raspberry Pi protecting herself through a Sarashikubi (gibbeted head) at MakerFaire

*I won't be talking about physical security today

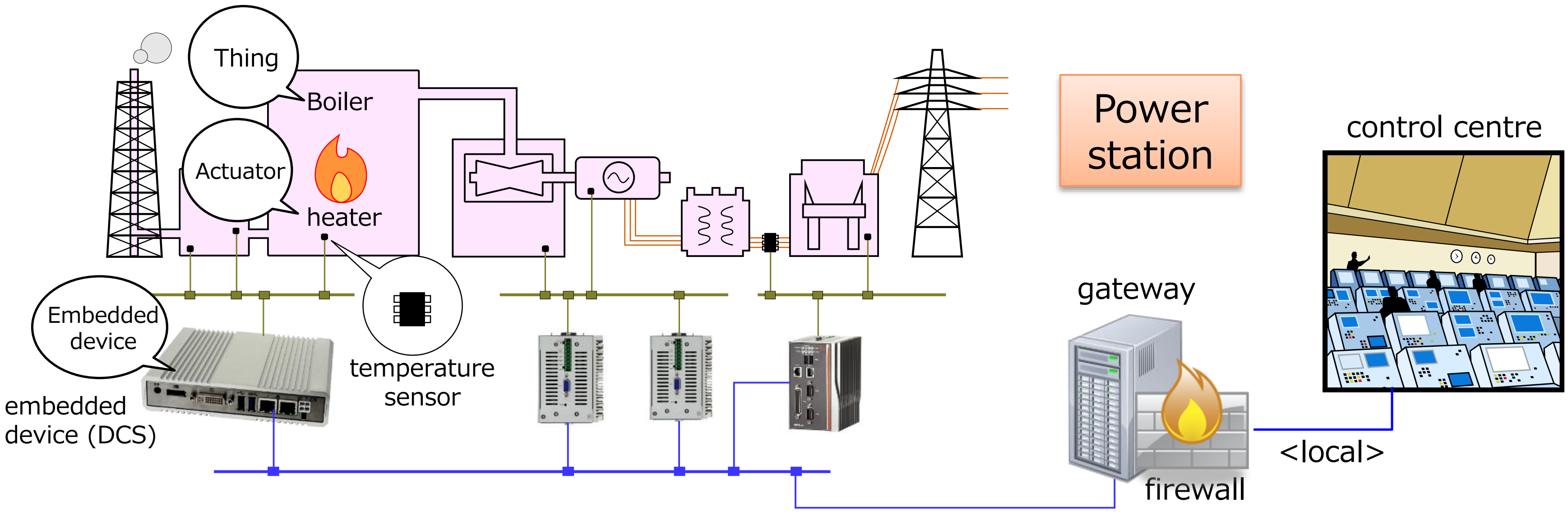
What's (on with) the IoT?

IoT (my simplified definition)

- A distributed computing system consisting of:
  - Embedded devices interacting with the physical world (*Things*) through sensors and actuators…
  - and connected to the cloud (eg: smart servers, PCs, other devices) through a network (eg: a virtual private network)…
  - in order to solve a problem or offer a service (eg: remote monitoring and control, optimization, automation, added value).

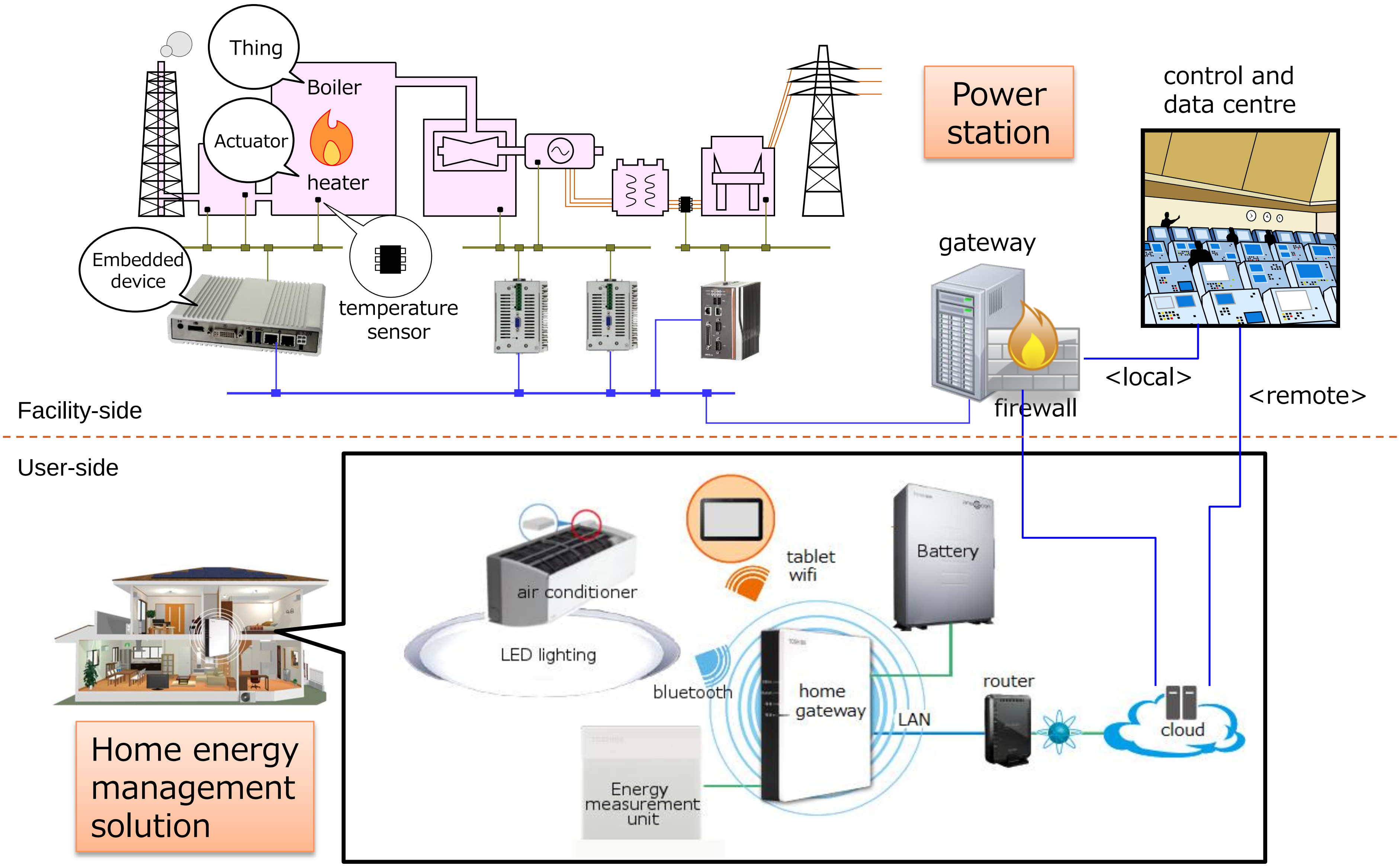
Data Source: Google Trends (www.google.com/trends)

Air gaps (the good old? times)



- **Not completely secure though**
  - Infected USB pendrives (eg: Stuxnet attack)
  - Insider attacks (unhappy employees, bribery, blackmail..)
  - Attacks to the source code repositories
  - Breaking into local Wifi networks through smartphones
    - or drones!

Going IoT (energy optimization)



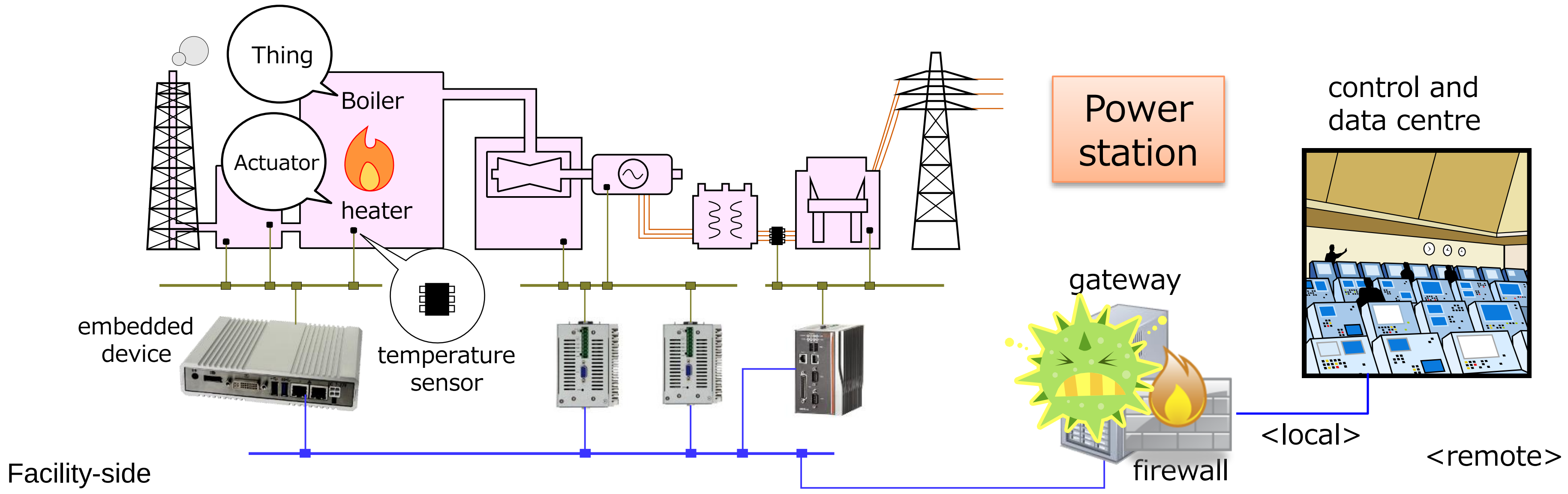
What we want to protect

- **Information security**
  - ➢ Authentication, integrity, confidentiality, availability..
    - Identity theft, privacy leaks, falsified energy usage..
- **Security impact on Safety**
  - ➢ Protect the “Things”
    - Nature, human lives, infrastructure, energy, equipment..

2007: Attack to the US power grid (industrial turbine spinning wildly out of control)

Source: US Department of Homeland Security

Facility-side embedded devices



Requirements

- Safety and high reliability
- Real-time response guarantees
- Software certification (tests, formal methods, ..)
- Continuous operation
- Fast booting

Practical constraints

- **Real-time requirements**
  - Weak to disturbances (DoS attacks)
- **Updating and re-certifying embedded software is costly**
  - Certified legacy software (~20 years untouched).
  - Rebooting can be expensive or dangerous (heating controller)
- **Fast booting**
  - Difficult to make it compatible with security booting
- **Low performance devices**
  - Some security countermeasures might cause too much overhead
- **Hardware-assisted security varies with the board**
  - Cortex-M3, Cortex-A9, PPC, SH, x86, x86_64..

(My) Three key security guidelines

1. **Reduce the attack surface**
   - Remove <u>anything</u> that is not used (not just restrict it to root)
   - Do you really need the ptrace system call?
     - or the kernel symbols, or modules, or gdb…
2. **Leverage the determinism of your system**
   - Look for anomalies that were supposed not to occur
     - Allows for security solutions that <u>generalize</u> to many attacks.
   - Example
     - Prevent new processes from being created in a real-time system.
     - Check the amount of network connections.
3. **Isolate critical software from less trustable software**
   - Reduce the impact of successful attacks

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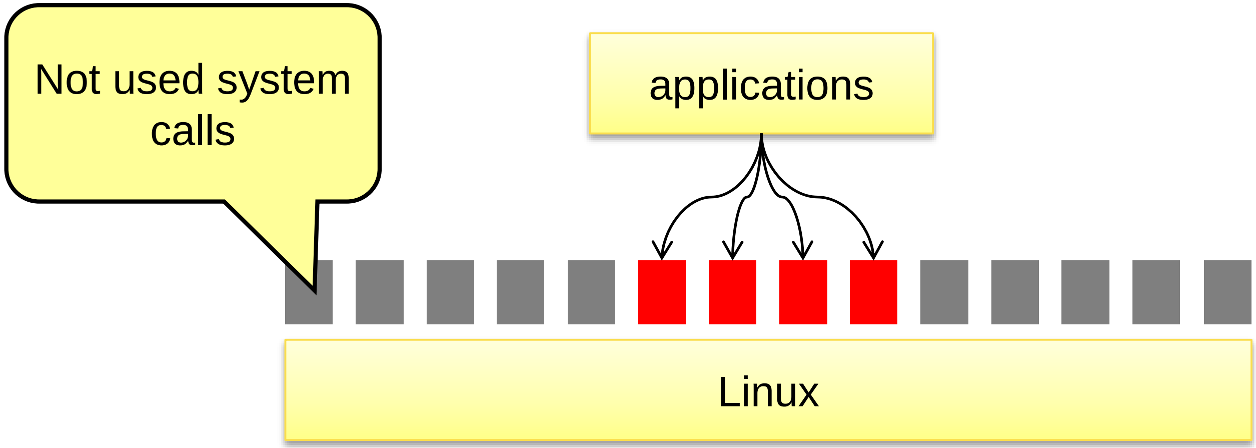
Remove anything unused

- **My point**
  - Unused interfaces are often the most vulnerable.
  - Attackers usually go for the lower hanging fruit.
- **Kernel**
  - System calls: ptrace, process_vm_write, iopl, _sysctl …
    - Harden the needed ones: mprotect (Grsecurity)
  - Information leaks: kallsyms, proc, sys, debugfs, kprobes…
  - Kernel trojans: /dev/kmem, modules, kexec, ksplice, …
- **File system customization**
  - RO filesystem with remounting disabled
  - Don’t install tools that are useful for attackers (unless required)
    - Objdump, perl, apt-get, mkfs, reboot

Use case: removing unused system calls

- **System calls**
  - The Linux kernel source code is complex and grows every minute.
  - Commonly used system calls are reasonably secure
    - Except those aimed at debugging, such as ptrace
  - But rarely used or recently introduced ones often contain bugs that may lead to security problems.



How to get rid of them

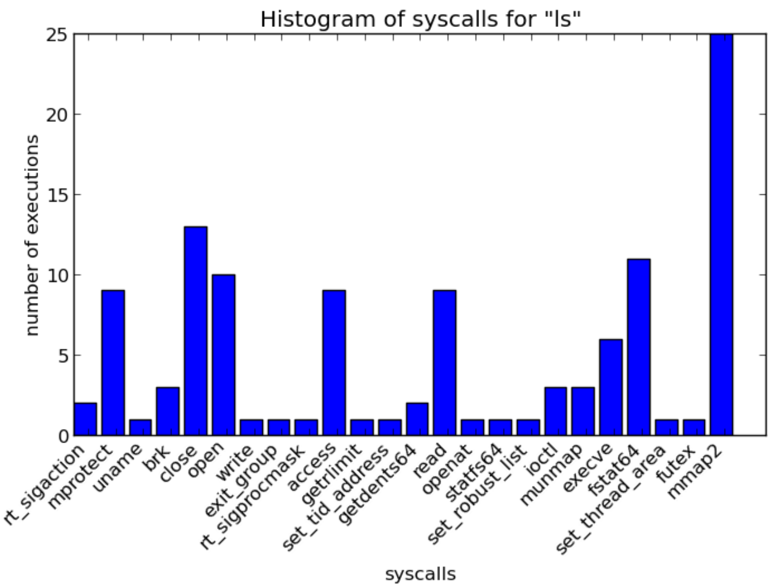
- **Step 1: syscall identification**
  - Tracing the application: see ./trace-syscalls.sh
  - Extract library calls (see libc-parser.py) and map them to syscalls
  - find-syscalls.py: https://github.com/tbird20d/auto-reduce (by Tim Bird)
- **Step 2: syscall removal**
  - Modify the kernel system call table (see below).
  - Kernel tinification: https://tiny.wiki.kernel.org/syscalls
  - Tim Bird patches: http://elinux.org/System_Size_Auto-Reduction

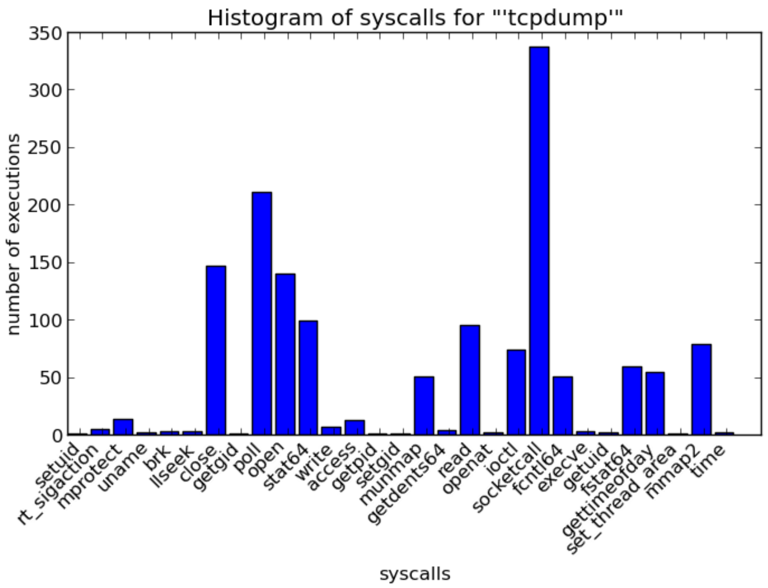
```
$ vi arch/x86/syscalls/syscalltbl.sh
  - linkat sys_linkat
  + linkat sys_ids_syscall
$ vi hello.c
  ret = linkat(AT_FDCWD, "hacker.txt", AT_FDCWD, "/etc/passwd", 0);
  if (ret != 0) perror("linkat");
$ ./hello.exe
  linkat: Function not implemented.
```

The system call was not executed. Optionally, we can be stealthy and return no error

Evaluation

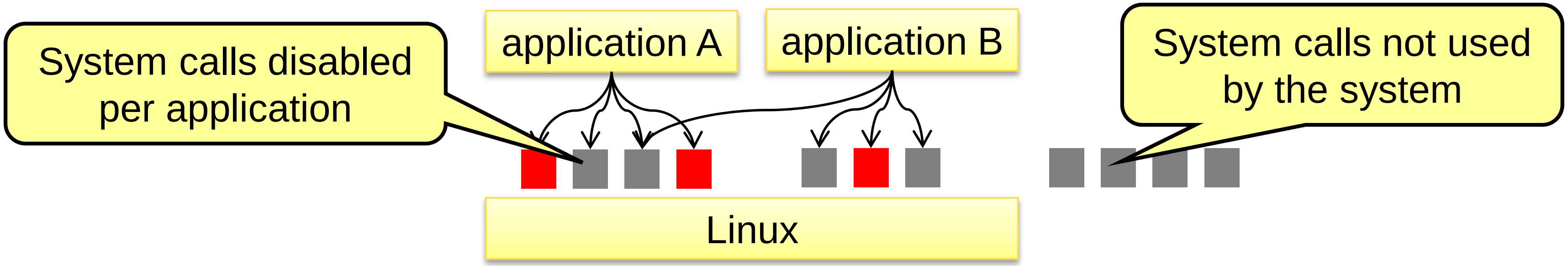
- **Percentage of system call attack surface reduction**
  - Simple applications such as ‘ls’ or ‘tcpdump’ only used about 30 unique system calls in average.
  - For x86, which has ~350 system calls, that represents a 91% reduction of the syscall attack surface.





Using seccom-bpf

- **Seccom-bpf (SECCOMP_SET_MODE_FILTER)**



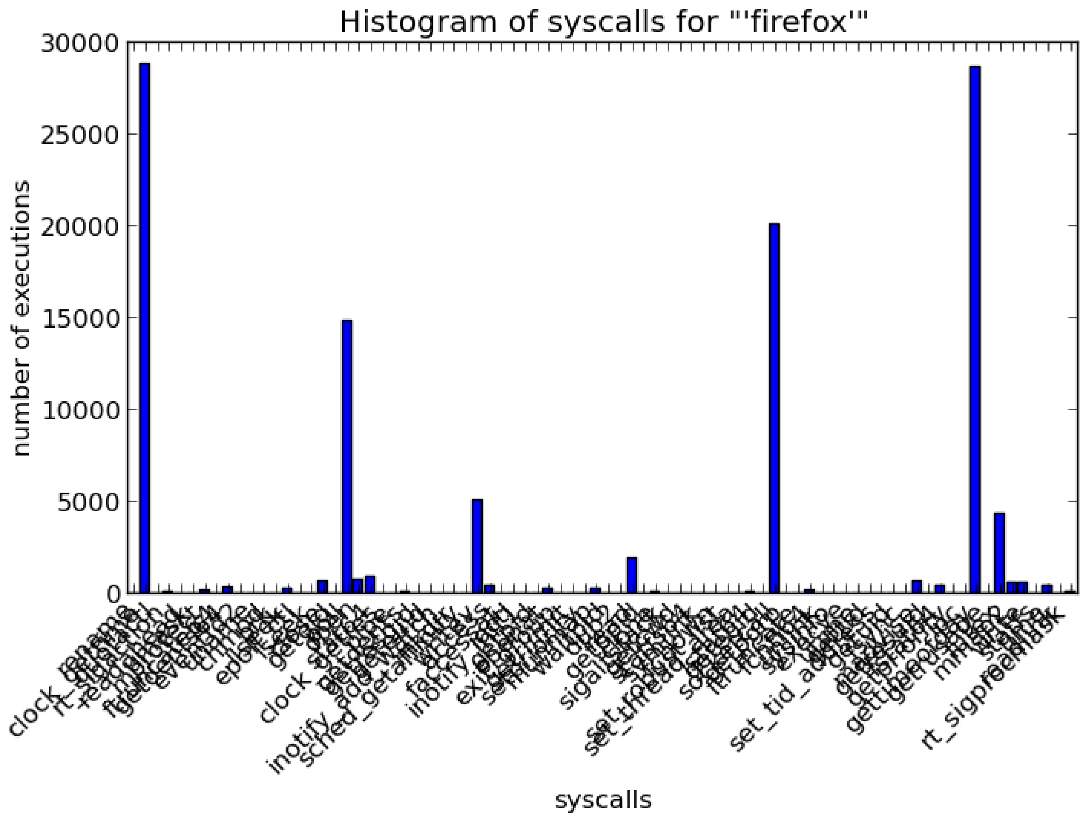

```
struct sock_filter filter[] = {
    ALLOW_SYSCALL(rt_sigreturn),
    ALLOW_SYSCALL(exit),
    ALLOW_SYSCALL(read),
    ALLOW_SYSCALL(write),
    ALLOW_SYSCALL(close),
    ...
};
struct sock_fprog prog = {
    .len = (unsigned short)(sizeof(filter)/sizeof(filter[0])),
    .filter = filter,
};
prctl(PR_SET_NO_NEW_PRIVS, 1, 0, 0, 0)
prctl(PR_SET_SECCOMP, SECCOMP_MODE_FILTER, &prog)

ret = syscall(69);
printf ("should not arrive here\n");
```

See bpf_syscall_error.c

There is more information we can use

- **Firefox (complex application)**
  - Note that the frequency depends greatly of the system call executed. This and other information can be used to refine the mechanism furthermore.



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Anomaly-based intrusion detection/prevention

- **Overview**
  - Leverage the determinism of your embedded systems
    - Detect anomalies that divert from expected behavior
- **What determinism?**
  - Task periods, maximum IRQs/s, task's CPU time per period
  - Device accesses: timing, order, allowed tasks
  - Fixed number of processes
  - Process sections' (text, GOT table) hashes
  - Files accessed by each application
  - Processes crashes shouldn't happen
  - Network: connections, packet patterns, packet sizes..

HIDS: Host-based intrusion detection systems

- **Syscall-based HIDS**
  - Track the execution of the system calls used by an application
    - Look for anomalies (eg syscall order, arguments, timing)
    - Small bound CPU overhead expected on the target application

```
1: open()
2: read()
3: setreuid()
4: mmap()
5: open()
6: write()
7: mmap()
```

Normal execution sequence

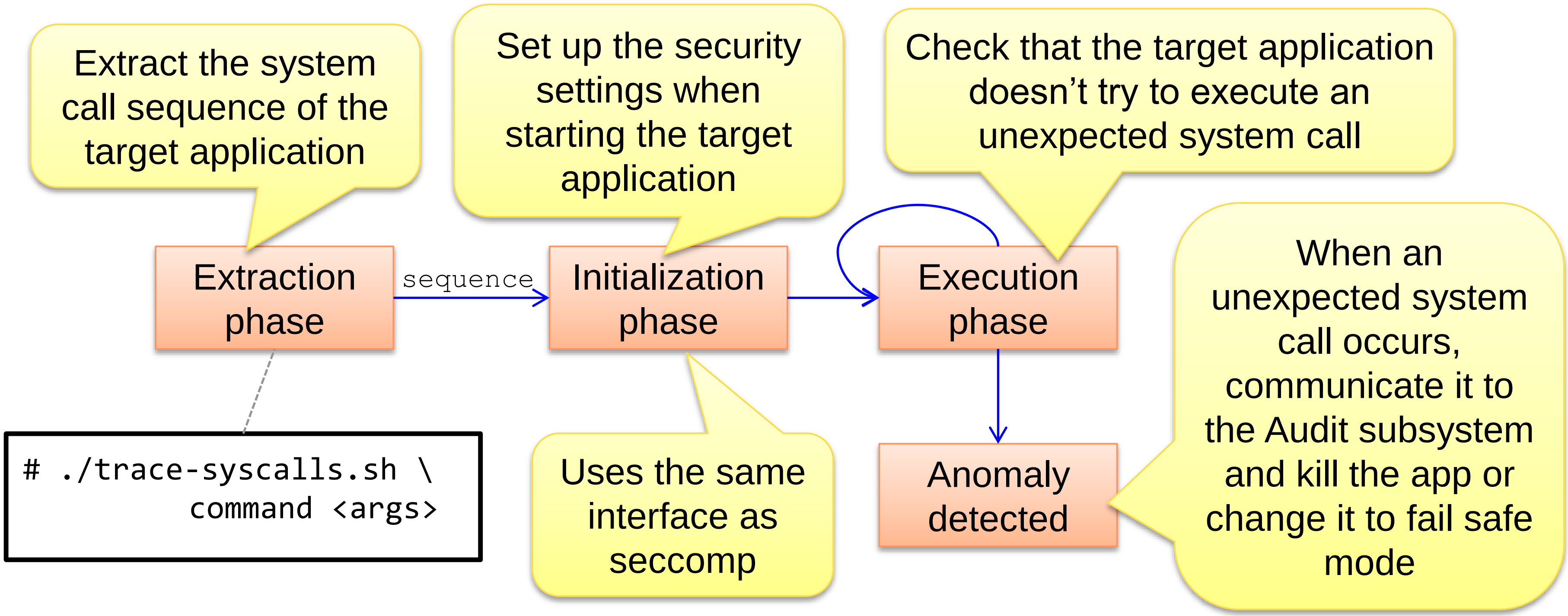
```
1: open()
2: read()
3: setreuid()
4: mmap()
5: open()
6: write()
7: mmap()
```

Stack overflow

```
3: mprotect()
4: mmap()
5: write()
```

Execution sequence after a stack overflow or ROP attack

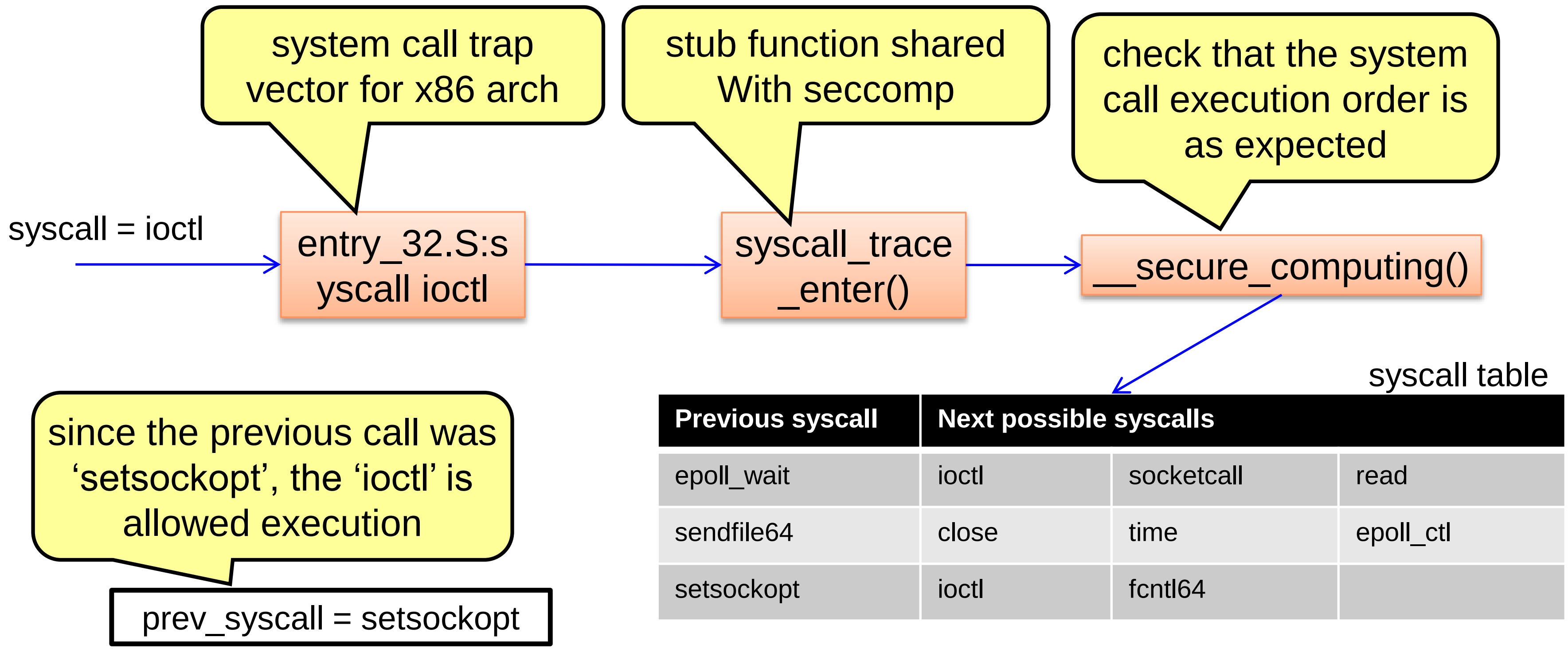
System call monitor (proof of concept)



Execution phase

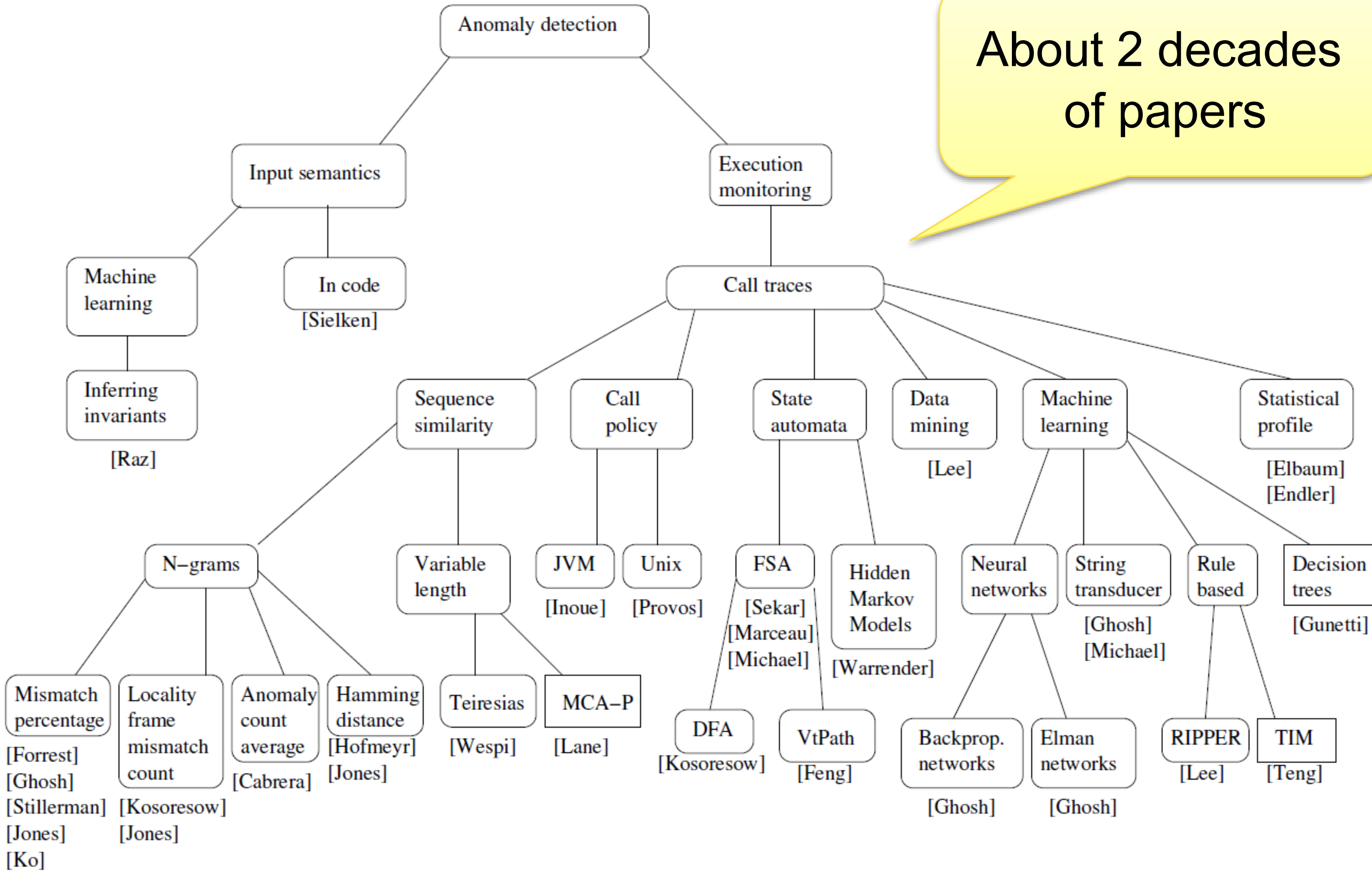
Monitoring

- During execution the system calls called by the target application need to be checked. This task is performed inside the kernel.
  - See 0002-syscall-hids-proof-of-concept-version-of-a-syscall-h.patch



Previous syscall	Next possible syscalls		
epoll_wait	ioctl	socketcall	read
sendfile64	close	time	epoll_ctl
setsockopt	ioctl	fcntl64	

Anomaly detection HIDS map



About 2 decades of papers

Source: Lea Viljanen. A survey of application level intrusion detection. (2004)

Integrity

- **Secure booting**
  - ROM → Bootloader → Kernel → Modules
- **File system integrity**
  - AIDE
  - Linux IMA/EVM
    - Check file and metadata integrity when the application is started
- **Problems:**
  - One-time checks
    - Rebooting devices or RT apps in a power station is not safe
  - React <u>after</u> the damage is done (prevention is best)
  - Does not address modifications to the process memory
    - There are are many ways to do that (even with DEP)

Inotify-based file integrity monitoring

- **Simple script that can be extended**

```python
import pyinotify
import sys
from mailer import send_sfm_report

wm = pyinotify.WatchManager()
mask = pyinotify.IN_ACCESS | pyinotify.IN_ATTRIB

class EventHandler(pyinotify.ProcessEvent):
    def process_default(self, event):
        send_sfm_report(event.pathname)

handler = EventHandler()
notifier = pyinotify.Notifier(wm, handler)
wdd = wm.add_watch(sys.argv[1], mask, rec=True)

notifier.loop()
```

See sfm.py

- **Other file operations to check**
  - IN_CREATE, IN_OPEN, …
- **Check for things that shouldn’t happen**
  - This way we can get security with no overhead in the common case

Attack to a memory resident app

Integrity of .text/.got/.got.plt data

- mprotect, GOT, buffer overflow attacks
- file integrity vs. memory integrity

line 31st

```
[ 1268.536643] line No.29      44630c08 39d872e8 b8905f0a 0885c074
[ 1268.536652] line No.30      0cc70424 d8fc0b08 e8b3dd05 00c60540
[ 1268.536660] line No.31      630c0801 83c4145b 5dc38db6 00000000
```

before attack

```
80481cd: 85 c0                   test   %eax,%eax
80481cf: 74 0c                   je     80481dd <__do_global_dtors_aux+0x5d>
80481d1: c7 04 24 98 03 0c 08    movl   $0x80c0398,(%esp)
80481d8: e8 f3 e4 05 00          call   80a66d0 <__deregister_frame_info>
80481dd: c6 05 a0 69 0c 08 01    movb   $0x1,0x80c69a0
80481e4: 83 c4 14                add    $0x14,%esp
80481e7: 5b                      pop    %ebx
80481e8: 5d                      pop    %ebp
80481e9: c3                      ret
80481ea: 8d b6 00 00 00 00       lea    0x0(%esi),%esi
```

'add' becomes 'nop'

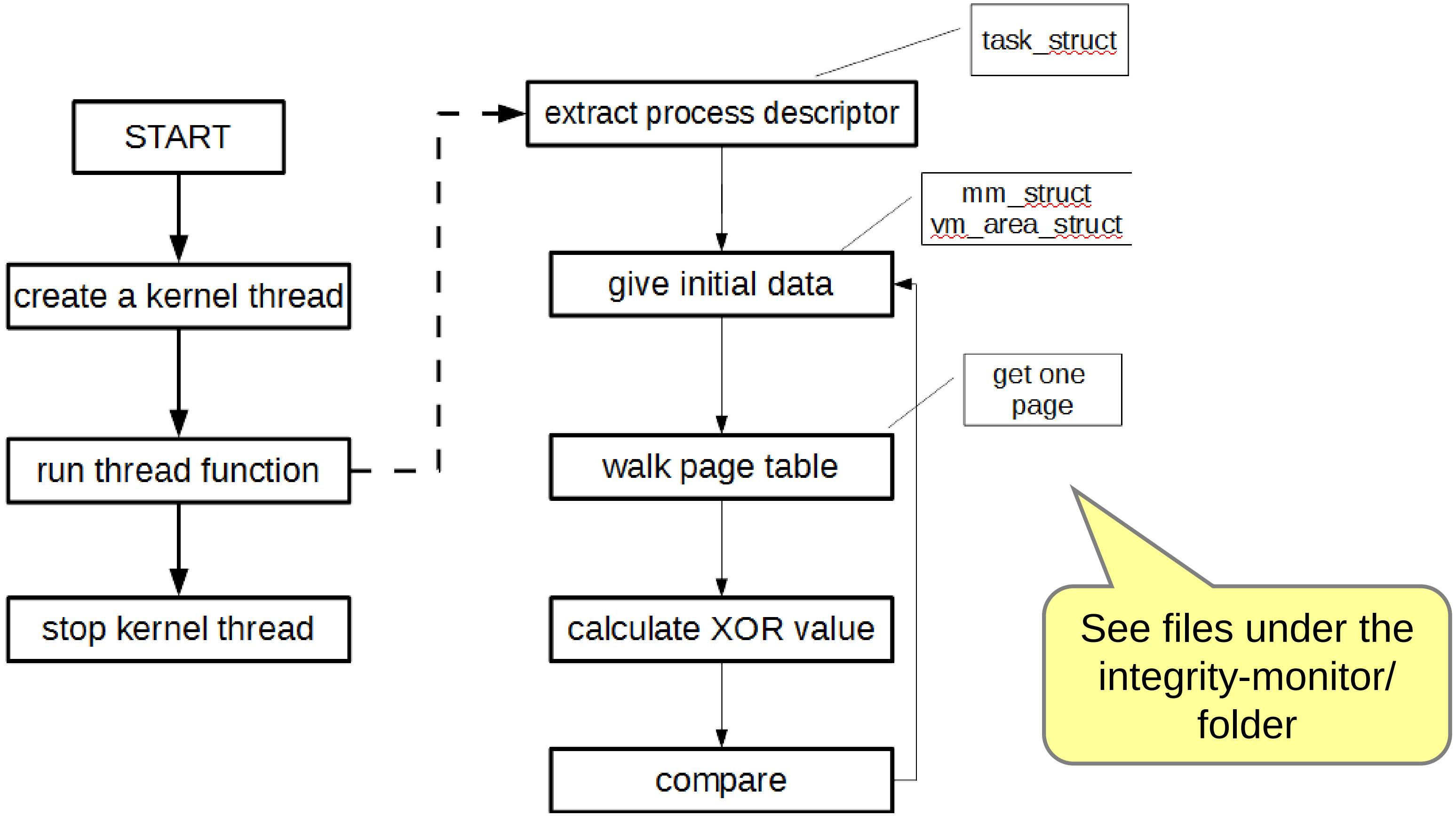
after attack

```
80481c8: b8 d0 66 0a 08          mov    $0x80a66d0,%eax
80481cd: 85 c0                   test   %eax,%eax
80481cf: 74 0c                   je     80481dd <__do_global_dtors_aux+0x5d>
80481d1: c7 04 24 98 03 0c 08    movl   $0x80c0398,(%esp)
80481d8: e8 f3 e4 05 00          call   80a66d0 <__deregister_frame_info>
80481dd: c6 05 a0 69 0c 08 01    movb   $0x1,0x80c69a0
80481e4: 90                      nop
80481e5: c4 14 5b                les    (%ebx,%ebx,2),%edx
80481e8: 5d                      pop    %ebp
80481e9: c3                      ret
80481ea: 8d b6 00 00 00 00       lea    0x0(%esi),%esi
```

Kernel integrity monitor (prototype)

Monitor flow chart

- Kernel thread running periodically in background



Note: XOR should be changed to a better hash algorithm

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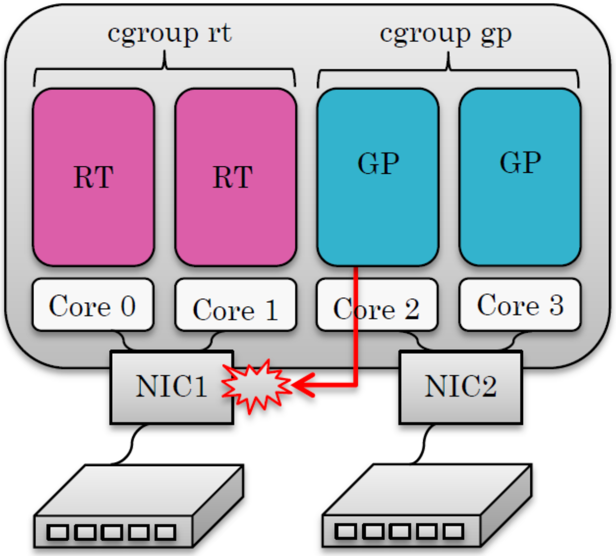
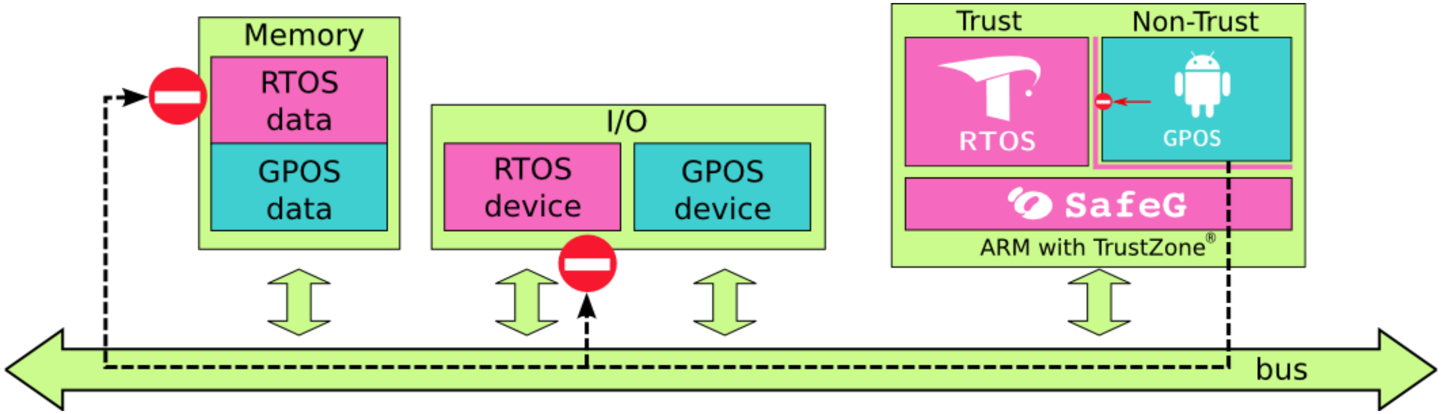
Linux partitioning

- **Containers**
  - Core isolation for the real-time performance of critical software
  - Restrict the amount of resources that less trustable software can use
  - Device cgroups: only block and character devices
    - See 0001-cgroups-devices-add-experimental-support-for-network.patch



Hardware-assisted architecture

- **SafeG (Nagoya University)**
  - Allows running an RTOS and Linux in parallel (single and multi-core)
  - Protection against peripheral DMA attacks.
  - Get it!
    - https://www.toppers.jp/safeg.html (日本語)
    - Latest: https://www.toppers.jp/download.cgi/safeg-1.0.tar.gz



Source: https://www.toppers.jp/safeg.html

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(My) Three key security guidelines

1. **Reduce the attack surface**
   - Remove <u>anything</u> that is not used (not just restrict it to root)
     - System call removal
     - Seccomp filter
2. **Leverage the determinism of your system**
   - Look for anomalies that were supposed not to occur
     - System call based kernel-level intrusion detector
     - File integrity monitor
     - Process memory integrity checker (kernel module)
3. **Isolate critical software from less trustable software**
   - Reduce the impact of successful attacks
     - Cgroup device kernel patch
     - SafeG (TrustZone monitor implementation)

A few things I didn't talk about

- **Cloud or user-side device's security**
  - Focus on the safety of the embedded devices at the "facility-side"
    - Eg: civil infrastructure systems (power, water, transport..)
- **Network security**
  - Cryptography, authentication, gateway, firewalls, NIDS (Snort)…
- **Access control**
  - Permissions, capabilities, suid, SELinux
- **Traditional anti-virus**
  - Focus on anomaly-based attack prevention systems
- **Hardening**
  - CFLAGS += "-fstack-protector -pie -fPIE -Wl,-z,relro -Wl,-z,now"
  - checksec.pl

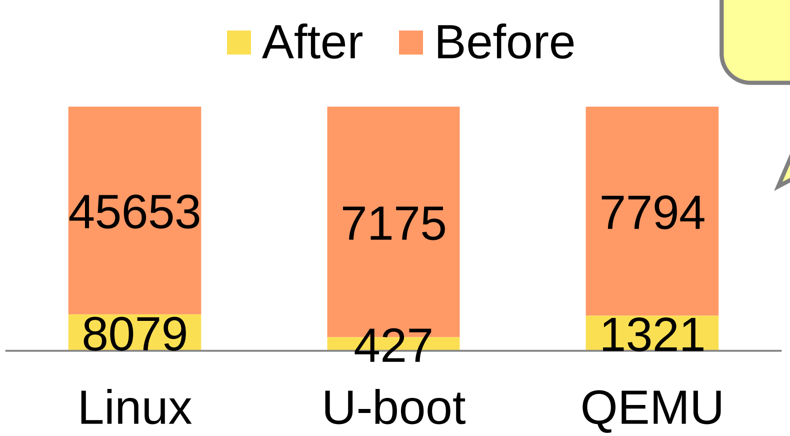
Future topics

- **Community software quality improvements**
  - Bug bounty programs, peer-reviews, formal methods..
- **Incident response**
  - What if secure booting detects a problem?
- **Attribution (tracking down the attackers)**
- **Coordinated node blacklisting**
  - Blacklist stolen or compromised nodes.
- **Stackable LSM (Linux Security Modules) and Seccomp**
  - Incompatibilities can be defined at Kconfig level
- **Safe and secure dynamic update technology**
- **Generic solutions (one ring to rule them all)**

On-going work

- **Simplify embedded security deployment**
  - We need to automatize know-how, patterns and best practices
    - Meta-security: kernel settings, busybox configuration, security tests (RIPE, checksec.pl, metasploitable, fuzzy), strip binaries..
- **Understand what your system is running**
  - RTOS developers are used to know everything the system has!
  - Make it easy to identify all inputs, attack surface
  - My small script: deadfile eliminator

See deadfile_eliminator-*.py (application agnostic)



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Thanks for your attention

Proof of concept code:
https://github.com/sangorrin/linuxcon-japan-2015