Trusted Execution Environments and how far you can trust them

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Jan Tobias Mühlberg, @jtmuehlberg

Short Bio:

- Research Manager at KU Leuven, imec-DistriNet
- PhD on software verification from Uni. of York, UK
- Since March 2011 at KU Leuven, Computer Science
- Topics
  - Hardware & Software Co-Design for Security
  - Embedded Systems Security, Safety-Critical Systems
  - Secure Processors & Trusted Computing
  - Automated Software Testing and Formal Verification
  - Sustainable Security

Building secure distributed applications

Lennert Wouters: “Security of embedded devices”

Mykyta Petik: “Implementing GDPR in software projects”

Jan Tobias Muehlberg: Trusted Computing

1. How to protect secure software at runtime
   . . . because not having vulnerabilities in your code may not be enough
2. Building security into distributed systems
3. Watch out for code-level vulnerabilities, side channels, etc.

Sebastian Deleersnyder: “Level up your threat modeling practice”

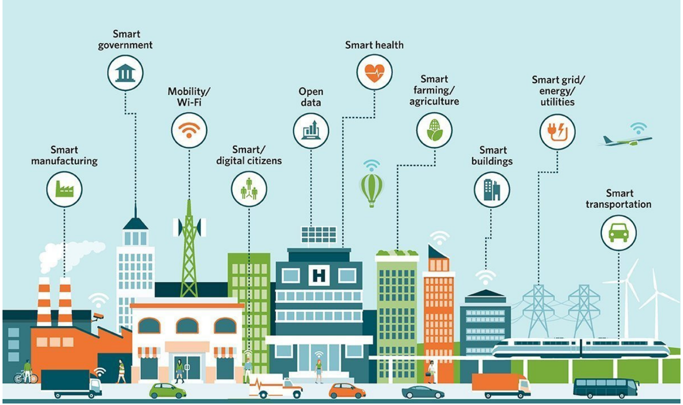
Isabelle Mauny: “The (bright) future of API security”

Review of Tuesday: Exploiting a Buffer Overflow

```c
/* stack1.c; https://github.com/gerasdf/InsecureProgramming */

#include <stdio.h>

int main() {
        int cookie;
        char buf[80];

        printf("buf: %08x cookie: %08x\n", &buf, &cookie);
        gets(buf);

        if (cookie == 0x41424344) {
                printf("you win!\n");
        }
}
```

Task: Compile and exploit to get “you win!”.

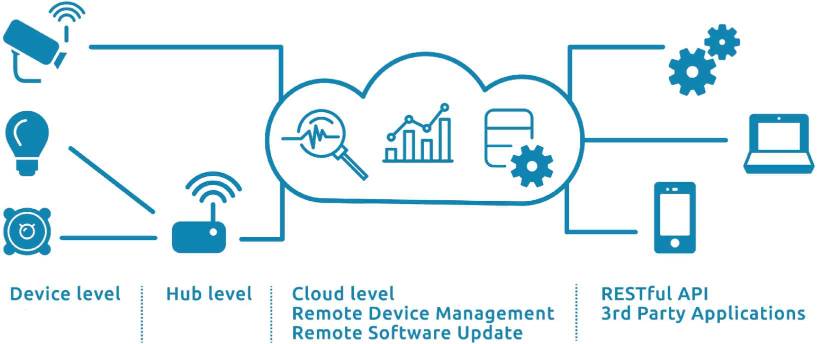
Security in Smart Environments



Infrastructure needs to be developed with safety, security and privacy in mind! What is critical infrastructure? What is critical code? Where is personal data being processed? What's the impact of failure?

Image source: `https://internetofthingsagenda.techtarget.com/definition/smart-city`

Security in Smart Environments



Understanding can be really difficult: What stake holders are involved? What are their objectives and abilities? What hardware and software is involved? Software quality? Data flows? Security requirements and guarantees?

Image source: `https://medium.com/connected-news/iot-foundation-what-is-an-iot-platform-c37c5e72d4a0`

Security in Smart Environments

Facebook Is Breached by Hackers, Putting 50 Million Users' Data at Risk

One of the challenges for Facebook's chief executive Mark Zuckerberg is convincing users that the company handles their data responsibly.

Source: `https://www.nytimes.com/2018/09/28/technology/facebook-hack-data-breach.html`

Security in Smart Environments

“The risks are about to get worse, because computers are being embedded into physical devices and will affect lives, not just our data.”

— Bruce Schneier, [Sch18]

Security in Smart Environments

WIRED

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Sex

The looming deluge of connected dildos is a security nightmare

Just because the teledildonics patent has expired, sex tech companies shouldn't rush to bring connectivity to their products

Source: `https://www.wired.co.uk/article/teledildonics-hacking-sex-toys` (2017)

Security in Smart Environments

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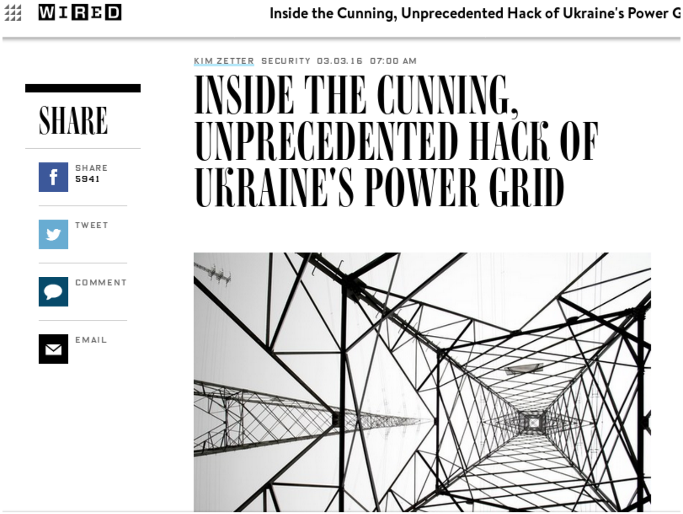
Smart dildos and vibrators keep getting hacked – but Tor could be the answer to safer connected sex

Connected sex toys are gathering huge amounts of data about our most intimate moments. Problem is, they're always getting hacked. Welcome to the emerging field of Onion Dildonics

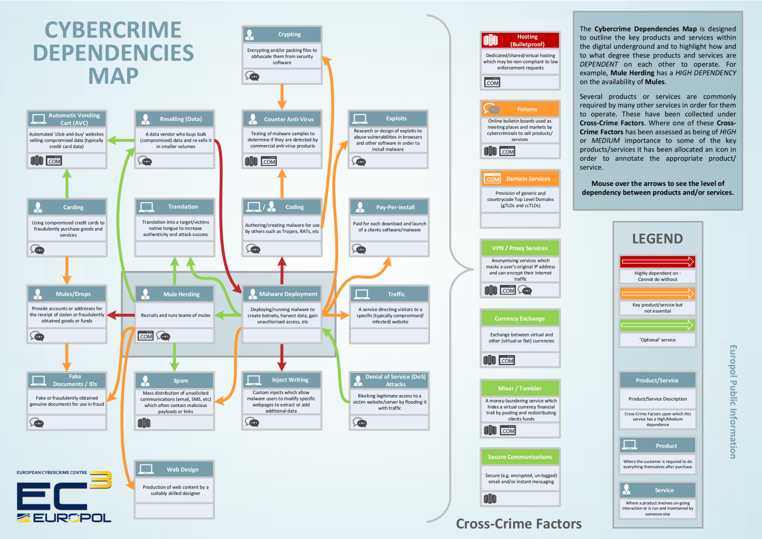
Source: `https://www.wired.co.uk/article/sex-toy-bluetooth-hacks-security-fix` (2018)

Security in Smart Environments



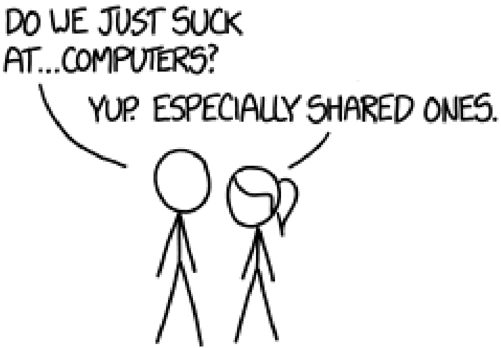
Source: `https://www.wired.com/2016/03/inside-cunning-unprecedented-hack-ukraines-power-grid/`

Security in Smart Environments



Source: `https://www.europol.europa.eu/publications-documents/cybercrime-dependencies-map`

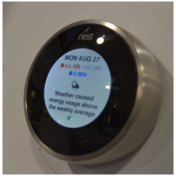
Security in Smart Environments



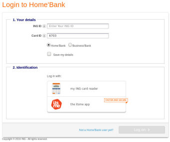
Source: `https://www.xkcd.com/1938/`

Security

1. **Understand the system.**
   - Context, hardware, software, data, users, use cases, etc.
2. **Understand the security requirements.**
   - Requirements are not features!
   - “Only authenticated users can do X.”
3. **Understand the attacker.**
   - “Attackers can listen to all communication, can drop, reorder or replay messages, may compromise Y% of the system, can’t break crypto.”
4. **Understand and embrace change!**
   - Discovery of vulnerabilities
   - Different understanding of the system
   - New (functional|security) requirements
   - New attacks, different attackers



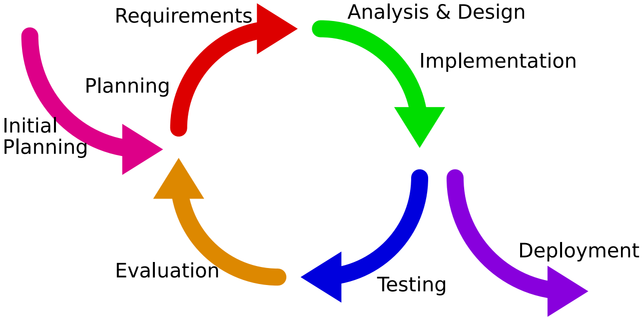







Source of images 1, 2, 3: `https://en.wikipedia.org/`

Security in the Software Development Life-Cycle



Understand the system • Understand the security requirements • Understand the attacker • Understand and embrace change!

Threat Modelling: Ask the right questions at the right moment, learn about attacks and defences, and argue why and when something is trustworthy.

What can we trust?

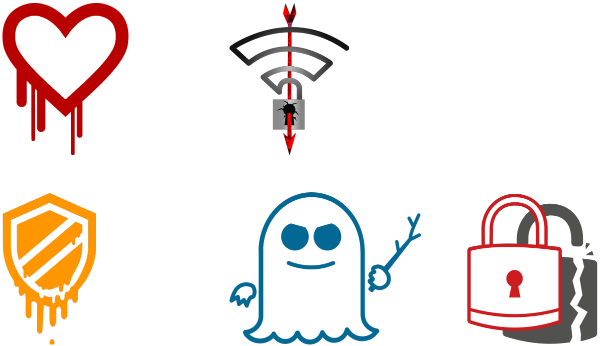
Software?

Hardware?

Supply Chains?

People?

...



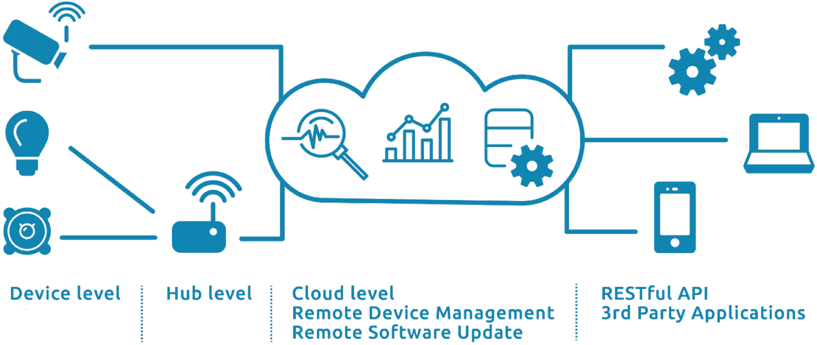
What can we trust?

- **Reasoning about security is about setting boundaries**
  - Which parts are considered trusted, and which parts are not?
  - How far do we want to go in defending your application?
  - What kind of security is economically viable?
- **Building secure systems requires rigorous security arguments**
  - Having a good idea about what you are building.
  - Determining which attackers are considered to be in scope.
  - Analysing potential vulnerabilities, and introducing appropriate countermeasures.
- **A security argument is a rigorous argument that under a given adversary model, a countermeasure effectively counters a threat, or a security mechanism achieves a security goal.**

What can we trust?

Source: https://www.bloomberg.com/news/features/2018-10-04/the-big-hack-how-china-used-a-tiny-chip-to-infiltrate-america...

Gathering Platform Requirements – A Thought Experiment



Sensors come from different vendors. Why would you trust them?
The cloud is "other people's computers". Why trust them?
Terminals may be used and managed by health care professionals. . .
There are huge software and hardware stacks with multiple vendors everywhere.

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Gathering Platform Requirements – A Thought Experiment

Reasoning about security is about setting boundaries!

Key elements of secure system design? Your choices?

- Get a cyber insurance!
- Thread modelling, risk assessment, etc.
- Anonymisation of data, if possible
- Zero Trust, micro-segmentation and granular perimeters

How can the execution environment (= mostly hardware) help you?

- Encryption
- Isolation, Security Rings
- Minimise Trusted Computing Base:
  remove hypervisors, OSs, libraries from TCB

Trusted Computing…

- Strong integrity protection and isolation for software components
- Software attestation: cryptographically bind a software to the executing hardware
- Sealed storage: bind data to attested software

…and how far you can trust it

- Under which assumptions and attacker models?
- What about privacy?
- What are interesting use cases?

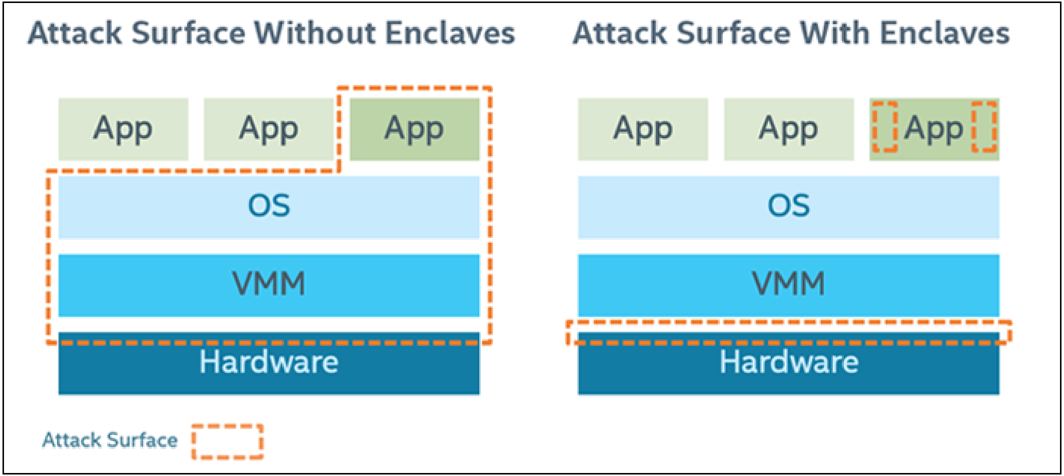
Gathering Platform Requirements – A Real System

“We don’t want the Signal service to have visibility into the social graph of Signal users. Signal is always aspiring to be as ‘zero knowledge’ as possible, and having a durable record of every user’s friends and contacts on our servers would obviously not be privacy-preserving.”

1. Run a contact discovery service in a secure SGX enclave.
2. Clients that wish to perform contact discovery negotiate a secure connection over the network all the way through the remote OS to the enclave.
3. Clients perform remote attestation to ensure that the code which is running in the *enclave is the same as the expected published open source code*.
4. Clients transmit [...] their address book to the enclave.
5. The enclave looks up a client’s contacts in the set of all registered users and encrypts the results back to the client.

Source: `https://signal.org/blog/private-contact-discovery/`

Motivation: Application Attack Surface



https://software.intel.com/en-us/articles/intel-software-guard-extensions-tutorial-part-1-foundation

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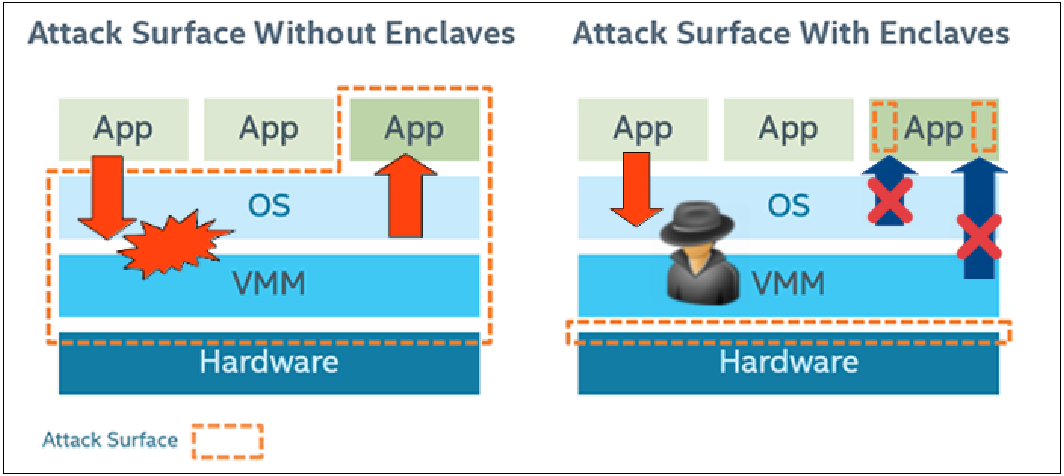

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Layered architecture ↔ **hardware-only TCB**

Comparing Hardware-Based Trusted Computing Architectures

	Isolation	Attestation	Sealing	Dynamic RoT	Code Confidentiality	Side-Channel Resistance	Memory Protection	Lightweight	Coprocessor	HW-Only TCB	Preemption	Dynamic Layout	Upgradeable TCB	Backwards Compatibility	Open-Source	Academic	Target ISA
AEGIS	●	●	●	●	●	○	●	○	○	●	●	●	○	●	○	●	–
TPM	○	●	●	○	●	–	◐	○	●	●	–	–	○	●	○	○	–
TXT	●	●	●	●	●	●	◐	○	●	●	○	●	○	●	○	○	x86_64
TrustZone	●	○	○	●	○	○	○	○	○	○	●	●	○	●	○	○	ARM
Bastion	●	○	●	●	●	○	●	○	○	○	●	●	●	●	○	●	UltraSPARC
SMART	○	●	○	●	○	–	○	●	○	○	–	–	○	●	○	●	AVR/MSP430
Sancus 1.0	●	●	○	●	○	●	○	●	○	●	○	○	○	●	●	●	MSP430
Soteria	●	●	○	●	●	●	○	●	○	●	○	○	○	●	●	●	MSP430
Sancus 2.0	●	●	○	●	●	●	○	●	○	●	◐	○	○	●	●	●	MSP430
SecureBlue++	●	○	●	●	●	○	●	○	○	●	●	●	○	●	○	○	POWER
SEV	●	●	●	●	●	○	●	○	○	○	●	●	●	●	○	○	x86_64
SGX	●	●	●	●	●	○	●	○	○	○	●	●	●	●	○	○	x86_64
Iso-X	●	●	○	●	○	○	●	○	○	○	●	●	●	●	○	●	OpenRISC
TrustLite	●	●	○	○	○	●	○	●	○	○	●	●	●	●	○	●	Siskiyou Peak
TyTAN	●	●	●	●	○	●	○	●	○	○	●	●	●	●	○	●	Siskiyou Peak
Sanctum	●	●	●	●	●	●	○	○	○	○	●	●	●	●	◐	●	RISC-V

● = Yes; ◐ = Partial; ○ = No; – = Not Applicable

Adapted from "Hardware-Based Trusted Computing Architectures for Isolation and Attestation", Maene et al., IEEE Transactions on Computers, 2017. [MGdC+17]

Trusted Computing

According to the *Trusted Computing Group*

Protect computing infrastructure at end points;
Hardware extensions to enforce specific behaviour and to provide cryptographic capabilities, protecting against unauthorised change and attacks

- **Endorsement Key**, EK Certificate, Platform Certificate: Unique private key that never leaves the hardware, authenticate device identity
- **Memory curtaining:** provide isolation of sensitive areas of memory
- **Sealed storage:** Bind data to specific device or software
- **Remote attestation:** authenticate hardware and software configuration to a remote host
- **Trusted third party** as an intermediary to provide (ano|pseudo)nymity

In practice: different architectures, subset of the above features, additions such as “enclaved” execution, memory encryption or secure I/O capabilities

Source: `https://en.wikipedia.org/wiki/Trusted_Computing`

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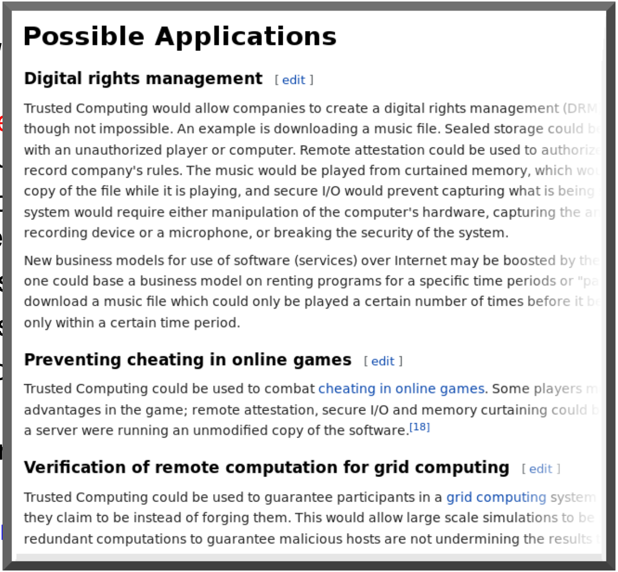


Possible Applications

Digital rights management [edit]

Trusted Computing would allow companies to create a digital rights management (DRM
though not impossible. An example is downloading a music file. Sealed storage could b
with an unauthorized player or computer. Remote attestation could be used to authoriz
record company's rules. The music would be played from curtained memory, which wo
copy of the file while it is playing, and secure I/O would prevent capturing what is being
system would require either manipulation of the computer's hardware, capturing the a
recording device or a microphone, or breaking the security of the system.

New business models for use of software (services) over Internet may be boosted by the
one could base a business model on renting programs for a specific time periods or "pa
download a music file which could only be played a certain number of times before it b
only within a certain time period.

Preventing cheating in online games [edit]

Trusted Computing could be used to combat cheating in online games. Some players m
advantages in the game; remote attestation, secure I/O and memory curtaining could b
a server were running an unmodified copy of the software.[18]

Verification of remote computation for grid computing [edit]

Trusted Computing could be used to guarantee participants in a grid computing system
they claim to be instead of forging them. This would allow large scale simulations to be
redundant computations to guarantee malicious hosts are not undermining the results

Source: `https://en.wikipedia.org/wiki/Trusted_Computing`

Trusted Computing

According to *Richard Stallman*

Treacherous Computing: “The technical idea underlying treacherous computing is that the computer includes a digital encryption and signature device, and the keys are kept secret from you. Proprietary programs will use this device to control which other programs you can run, which documents or data you can access, and what programs you can pass them to. These programs will continually download new authorisation rules through the Internet, and impose those rules automatically on your work.”

In the light of recent incidents…

- **Buggy software:** think of OpenSSL’s Heartbleed in an enclave
- **Side channels:** timing, caching, speculative execution, etc.
- **Buggy system:** CPUs, peripherals, firmware (Broadpwn, Intel ME, Meltdown)
- **Malicious intent:** Backdoors, ransomware, etc.

Source: `https://www.gnu.org/philosophy/can-you-trust.html`

Trusted Computing (and why Sancus?)

Good design practice for trusted computing?
Good use cases for trusted computing?

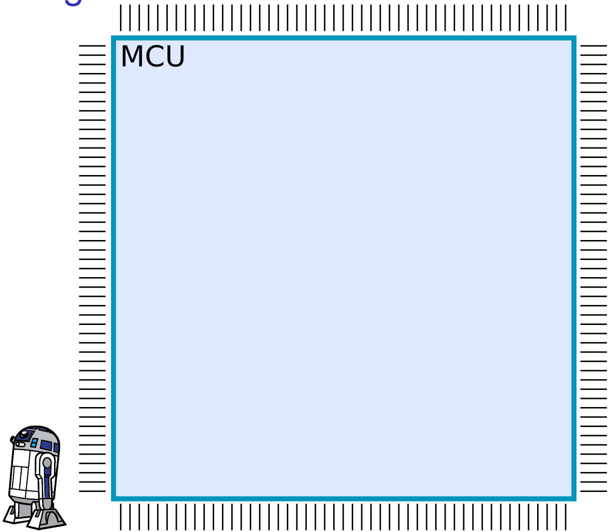
- non-invasive, understandable, measurably secure
- stuff that matters: critical applications, critical infrastructure, embedded

Don’t restrict the user but enable them, convince them to trust.
Build to validate, invite to scrutinise: hardware and software.
Build upon well-understood OSS building blocks: hardware, crypto, compilers, OS, libs
Divide and conquer: memory curtaining and isolation make validation easier

Source: `https://twitter.com/MelissaKaulfuss/status/804209915109376007s=09`

Isolation and Attestation on Light-Weight MCUs

Many microcontrollers feature little security functionality



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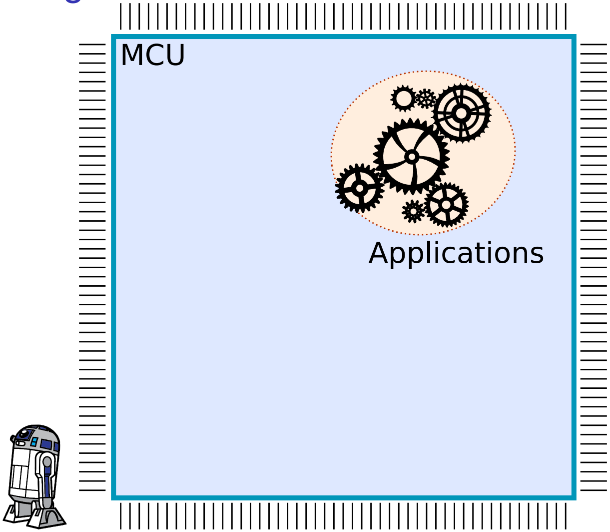

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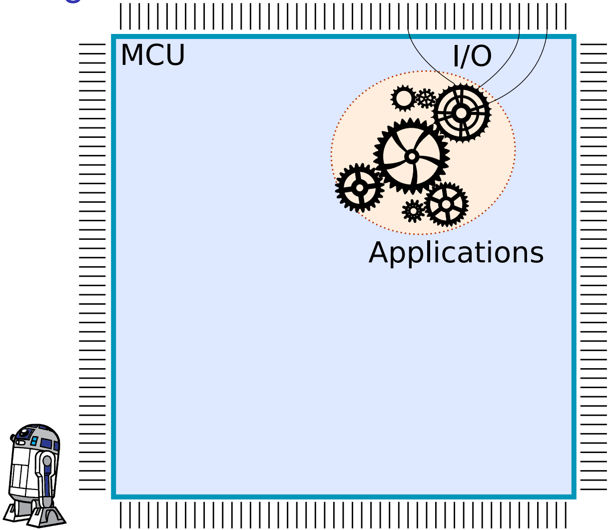

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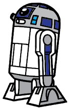

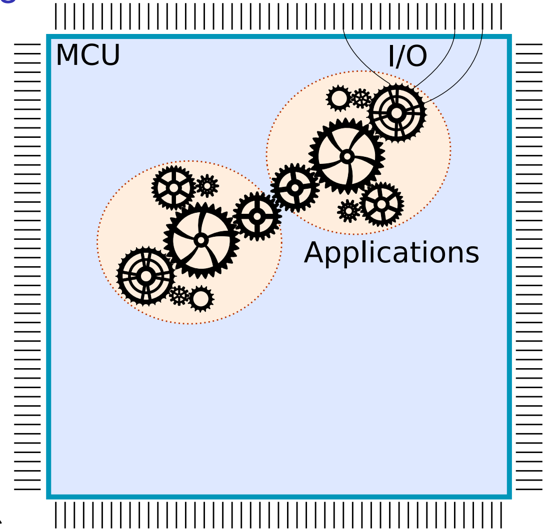

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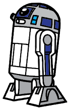
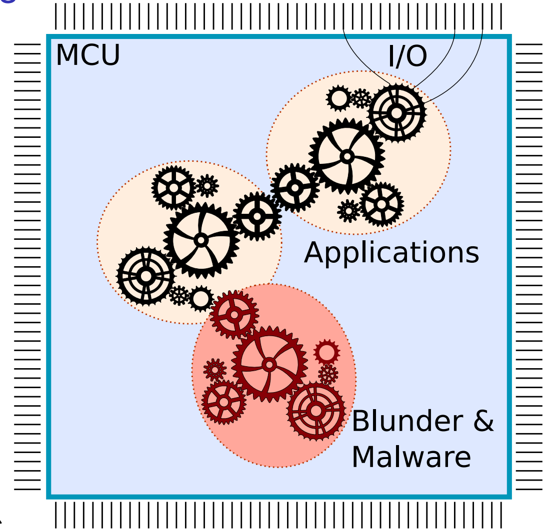
- Boundaries between applications are not enforced





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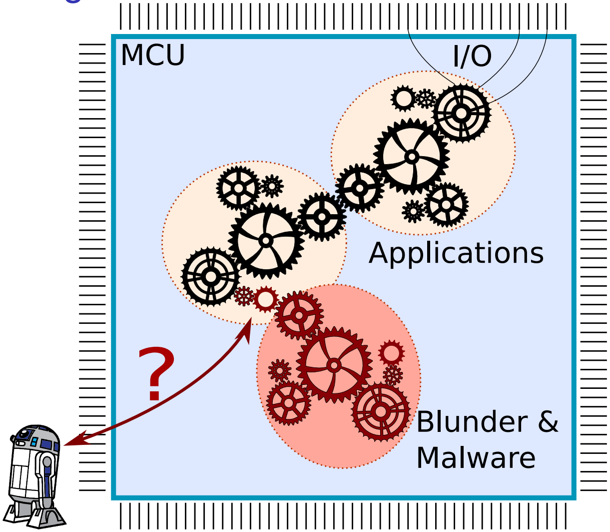

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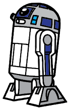
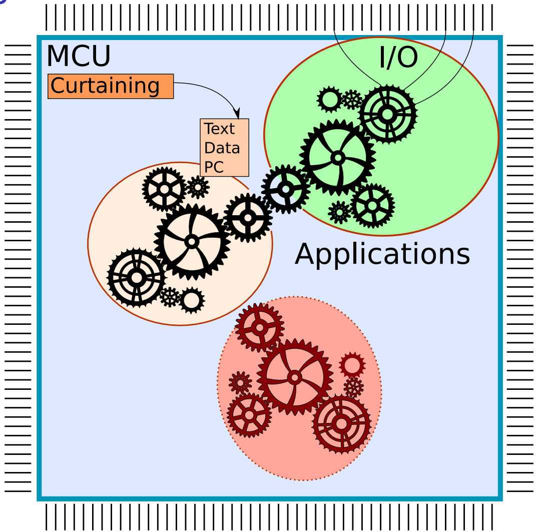
- Strong isolation, restrictive interfaces, exclusive I/O





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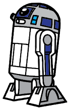

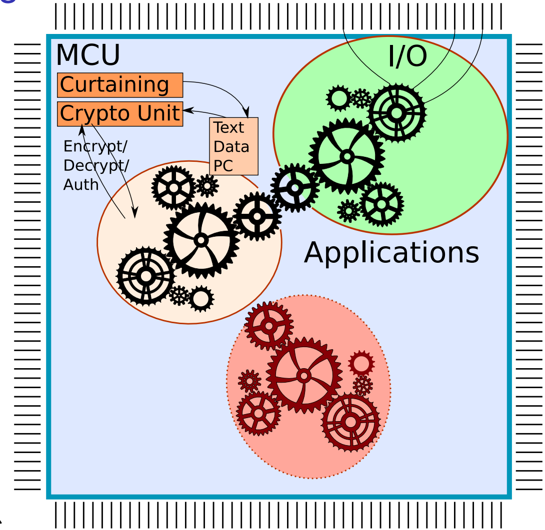

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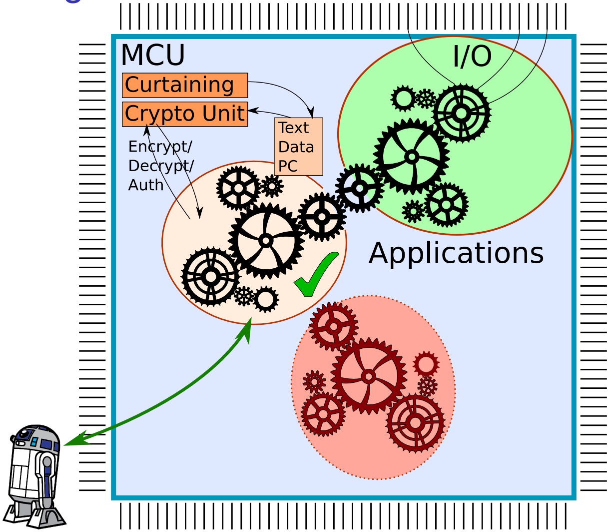

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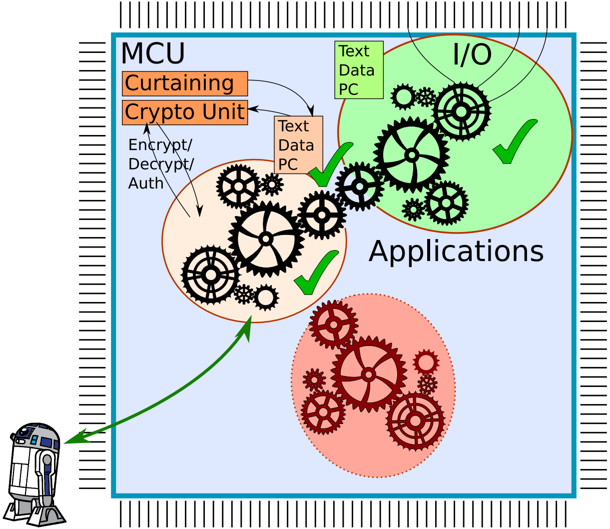
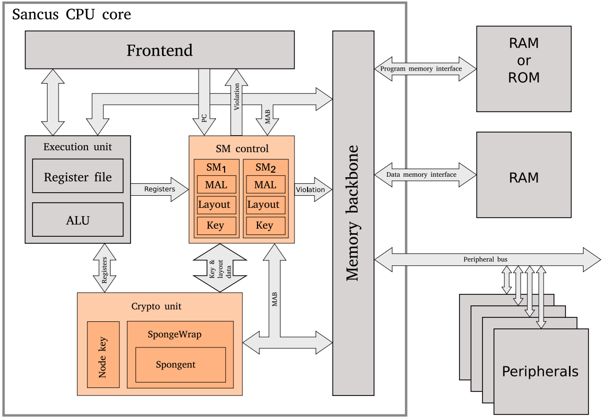


Sancus: Strong and Light-Weight Embedded Security [NVBM+17]

Extends openMSP430 with strong security primitives

- Software Component Isolation
- Cryptography & Attestation
- Secure I/O through isolation of MMIO ranges



Efficient

- Modular, $\leq$ 2 kLUTs
- Authentication in μs
- $+$ 6% power consumption

Cryptographic key hierarchy for software attestation

Isolated components are typically very small ($<$ 1kLOC)

Sancus is Open Source: https://distrinet.cs.kuleuven.be/software/sancus/

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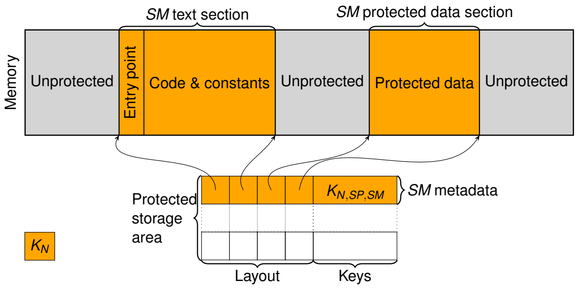
- $+$ 6% power consumption

Cryptographic key hierarchy for software attestation

N = Node; *SP* = Software Provider / Deployer
SM = protected Software Module (== enclave)



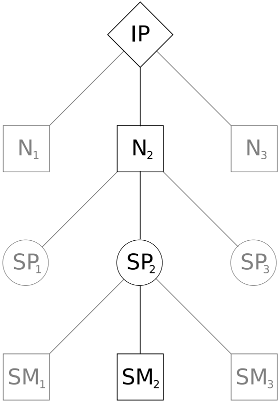
Isolated components are typically very small (< 1kLOC)

Sancus is Open Source: https://distrinet.cs.kuleuven.be/software/sancus/

Attestation and Communication with Sancus

Ability to use $K_{N,SP,SM}$ proves the integrity and isolation of *SM* deployed by *SP* on *N*

- Only *N* and *SP* can compute $K_{N,SP,SM}$
  N knows K_N and *SP* knows K_{SP}
- $K_{N,SP,SM}$ on *N* is computed after enabling isolation
  No isolation, no key; no integrity, wrong key
- Only *SM* on *N* is allowed to use $K_{N,SP,SM}$
  Through special instructions



Remote attestation and secure communication by Authenticated Encryption with Associated Data

- Confidentiality, integrity and authenticity
- Encrypt and decrypt instructions use $K_{N,SP,SM}$ of the calling SM
- Associated Data can be used for nonces to get freshness

Comparing Hardware-Based Trusted Computing Architectures

	Isolation	Attestation	Sealing	Dynamic RoT	Code Confidentiality	Side-Channel Resistance	Memory Protection	Lightweight	Coprocessor	HW-Only TCB	Preemption	Dynamic Layout	Upgradeable TCB	Backwards Compatibility	Open-Source	Academic	Target ISA
AEGIS	●	●	●	●	●	○	●	○	○	●	●	●	○	●	○	●	–
TPM	○	●	●	○	●	–	◐	○	●	●	–	–	○	●	○	○	–
TXT	●	●	●	●	●	●	◐	○	●	●	○	●	○	●	○	○	x86_64
TrustZone	●	○	○	●	○	○	○	○	○	○	●	●	○	●	○	○	ARM
Bastion	●	○	●	●	●	○	●	○	○	○	●	●	●	●	○	●	UltraSPARC
SMART	○	●	○	●	○	–	○	●	○	○	–	–	○	●	○	●	AVR/MSP430
Sancus 1.0	●	●	○	●	○	●	○	●	○	●	○	○	○	●	●	●	MSP430
Soteria	●	●	○	●	●	●	○	●	○	●	○	○	○	●	●	●	MSP430
Sancus 2.0	●	●	○	●	●	●	○	●	○	●	◐	○	○	●	●	●	MSP430
SecureBlue++	●	○	●	●	●	○	●	○	○	●	●	●	○	●	○	○	POWER
SEV	●	●	●	●	●	○	●	○	○	○	●	●	●	●	○	○	x86_64
SGX	●	●	●	●	●	○	●	○	○	○	●	●	●	●	○	○	x86_64
Iso-X	●	●	○	●	○	○	●	○	○	○	●	●	●	●	○	●	OpenRISC
TrustLite	●	●	○	○	○	●	○	●	○	○	●	●	●	●	○	●	Siskiyou Peak
TyTAN	●	●	●	●	○	●	○	●	○	○	●	●	●	●	○	●	Siskiyou Peak
Sanctum	●	●	●	●	●	●	○	○	○	○	●	●	●	●	◐	●	RISC-V

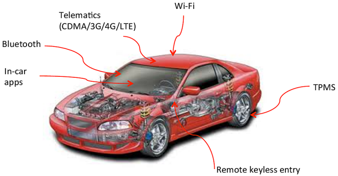
● = Yes; ◐ = Partial; ○ = No; – = Not Applicable

Adapted from "Hardware-Based Trusted Computing Architectures for Isolation and Attestation", Maene et al., IEEE Transactions on Computers, 2017. [MGdC+17]

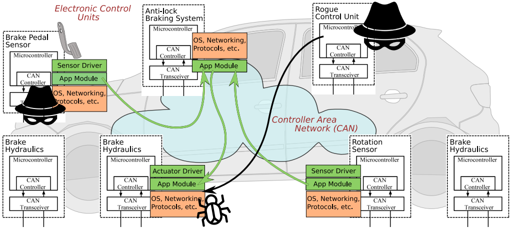
Secure Automotive Computing with Sancus [VBMP17]

Modern cars can be hacked!

- Network of more than 50 ECUs
- Multiple communication networks
- Remote entry points
- Limited built-in security mechanisms



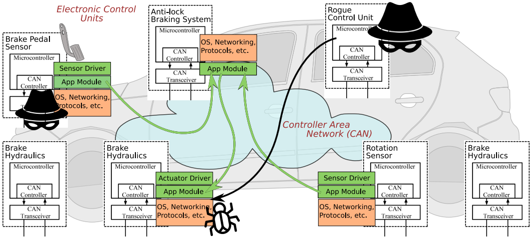
Miller & Valasek, “Remote exploitation of an unaltered passenger vehicle”, 2015



Sancus brings strong security for embedded control systems:

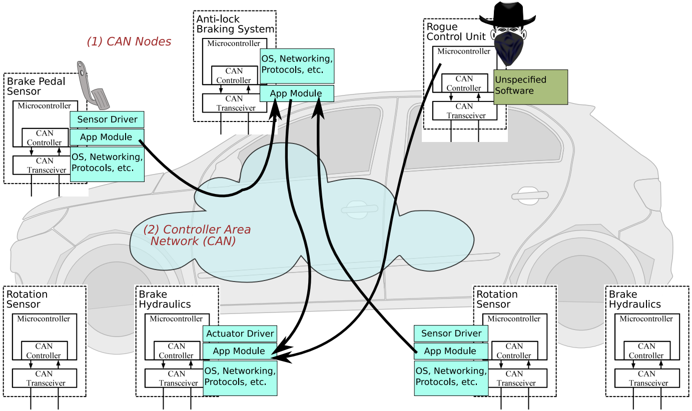
- Message authentication
- Trusted Computing: software component isolation and cryptography
- Strong software security
- Applicable in automotive, ICS, IoT, . . .

Secure Automotive Computing with Sancus [VBMP17]



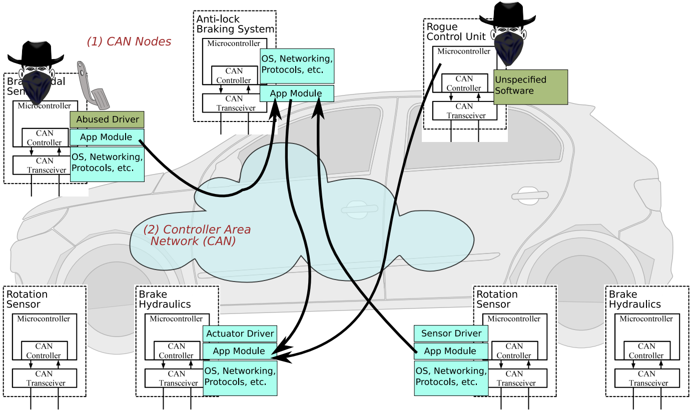
VulCAN: Generic design to exploit light-weight TC in CAN-based control networks; `https://distrinet.cs.kuleuven.be/software/vulcan/`
Implementation: based on Sancus [NVBM^{+}17]; we implement, strengthen and evaluate authentication protocols, vatiCAN [NR16] and LeiA [RG16]

Attacking the CAN



Complex bus system with many ECUs and gateways to other communication systems; no protection against message injection or replay attacks.
→ Message Authentication; specified in AUTOSAR, proposals: vatiCAN, LeiA; no efficient and cost-effective implementations yet

Attacking CAN Message Authentication

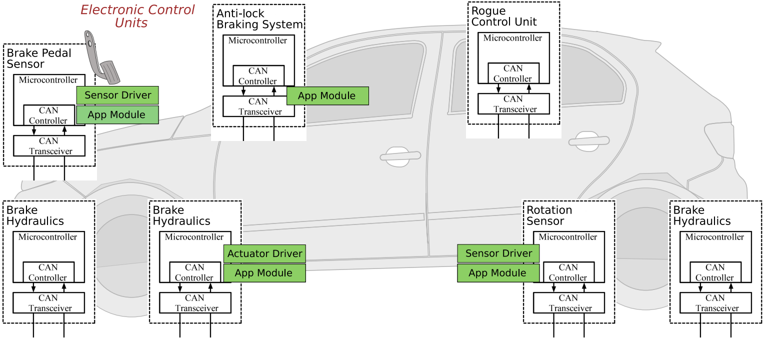


What about Software Security?

Lack of security mechanisms on light-weight ECUs leverages software vulnerabilities: attackers may be able to bypass encryption and authentication.

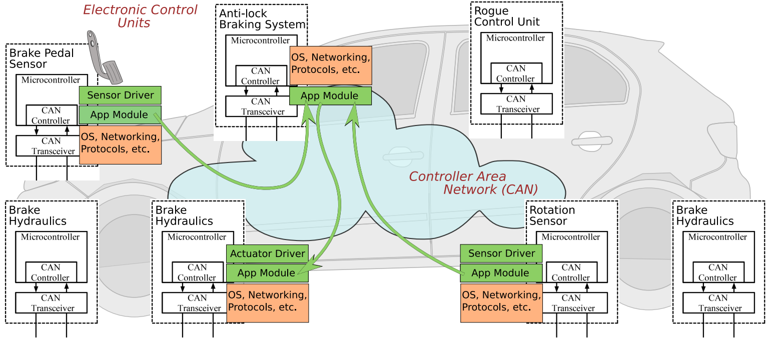
→ Software Component Authentication & Isolation

Vulcanising Distributed Automotive Applications



- Critical application components in enclaves: software isolation + attestation

Vulcanising Distributed Automotive Applications



- Critical application components in enclaves: software isolation + attestation
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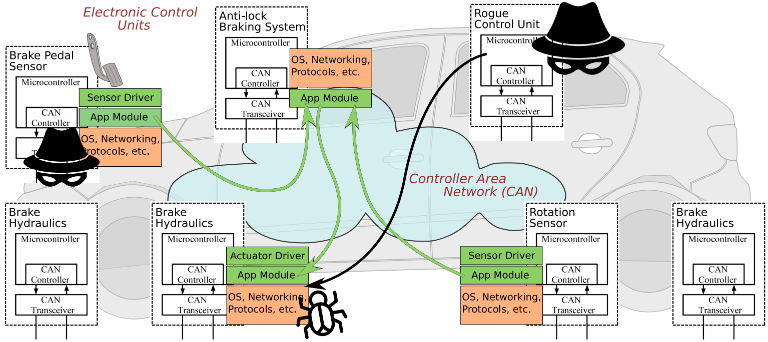
Vulcanising Distributed Automotive Applications



- Critical application components in enclaves: software isolation + attestation
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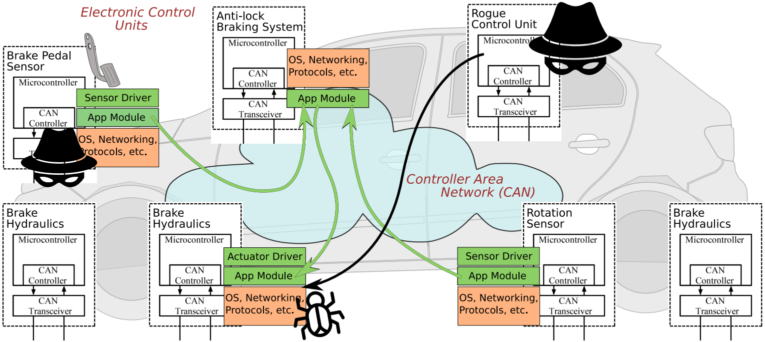
Vulcanising Distributed Automotive Applications



- Critical application components in enclaves: software isolation + attestation
- Authenticated CAN messages over untrusted system software/network
- Rogue ECUs, software attackers and errors in untrusted code cannot interfere with security, but may harm availability
- Infrastructure support: isolation, attestation, fast crypto – **Sancus**

Authentic Execution of Distributed Event-Driven Applications




"End-to-End Security for Distributed Event-Driven Enclave Applications on Heterogeneous TEEs", Scopelliti & Pouyanrad et al. [SPN+22, NMP17]

Trusted Execution for Everyone

Fortanix solves cloud security and privacy using runtime encryption technology build upon Intel SGX. `https://fortanix.com/`

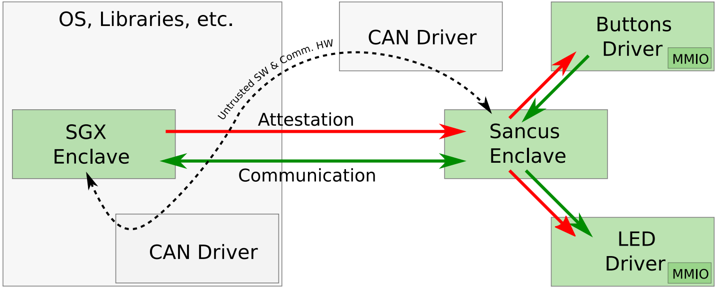
SCONE enables secure execution of containers and programs using Intel SGX. `https://sconecontainers.github.io/`

Graphene-SGX: A practical library OS for unmodified applications on SGX. `https://github.com/oscarlab/graphene`

Open Enclave is an SDK for building enclave applications in C and C++. `https://github.com/Microsoft/openenclave`

Our Tutorial: Building distributed enclave applications with Sancus and SGX `https://github.com/sancus-pma/tutorial-dsn18`

Tutorial Overview – Learning Outcomes



Programming Enclaves

- Remote attestation
- ECALLs and OCALLs
- Untrusted pointers
- Secure random numbers
- Local attestation
- Secure I/O

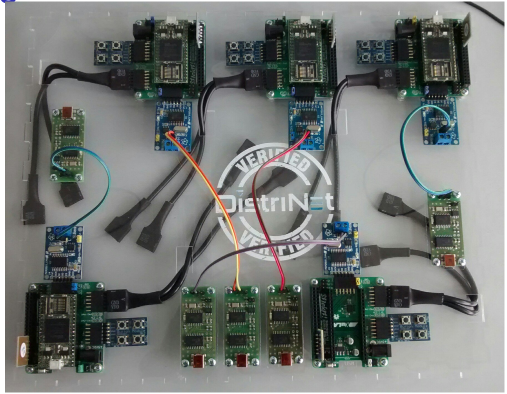
Tricky bits

- Sanitising untrusted pointers
- Information leakage and side channels
- Freshness and non-repudiation: nonces and session keys
- Attesting SGX enclaves – what is the root of trust?

Concepts

- Authentic Execution: end-to-end security for distributed applications on heterogeneous TEEs

Tutorial Overview – Learning Outcomes



Programming Enclaves

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Concepts

- Authentic Execution: end-to-end security for distributed applications on heterogeneous TEEs

When not to trust your TEE...

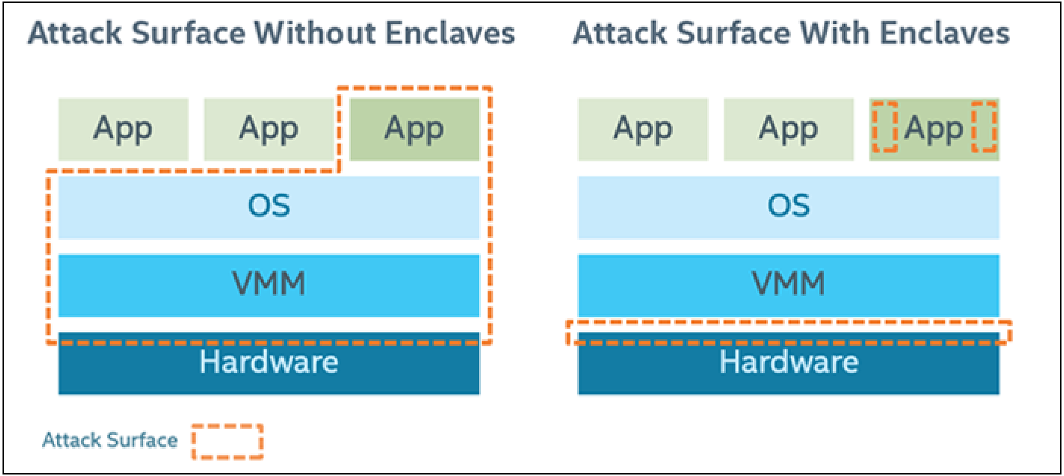
Trusted Execution does not help you against bugs in your own (trusted) code.

Trusted Execution does not help you if you don't know what to protect.

Enclaves may inherit vulnerabilities from SDKs, libraries, and from the hardware.

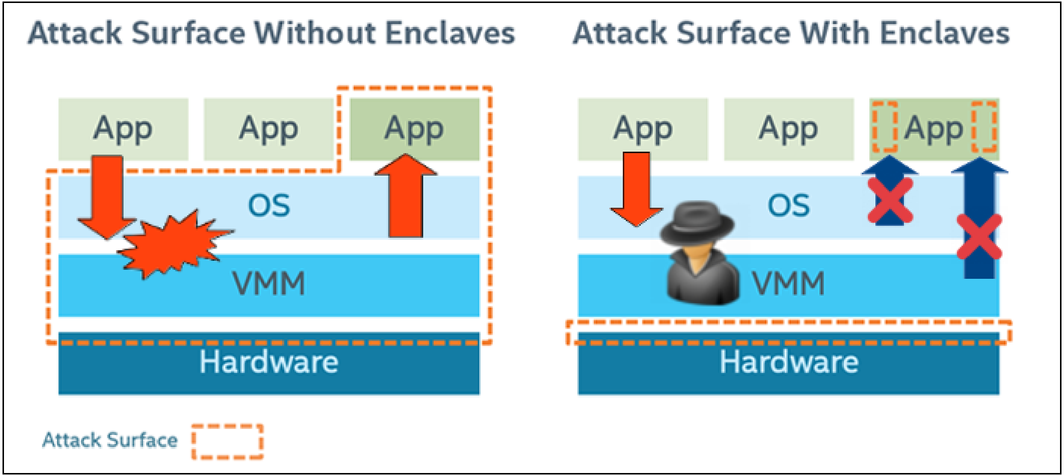
(Trusted) Execution can be observed through indirect channels and may leak secrets through these channels.

Motivation: Application Attack Surface



https://software.intel.com/en-us/articles/intel-software-guard-extensions-tutorial-part-1-foundation

Motivation: Application Attack Surface



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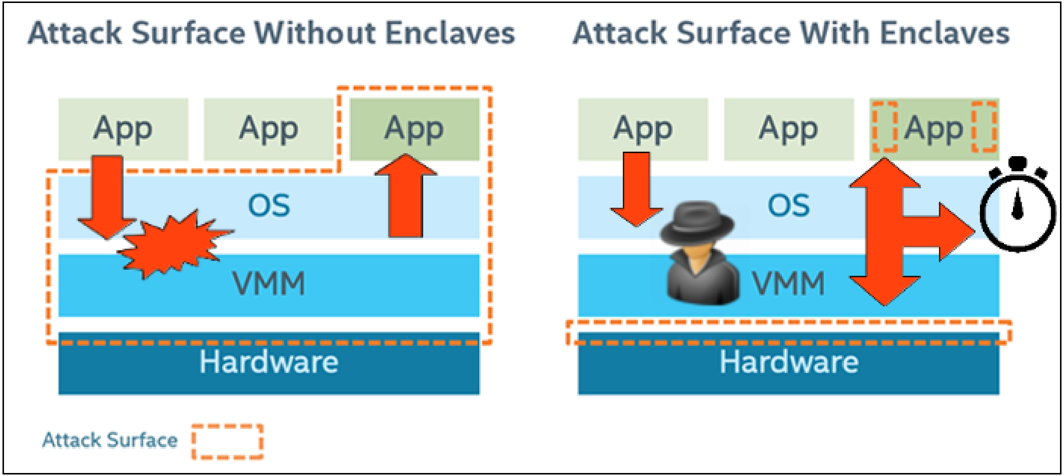

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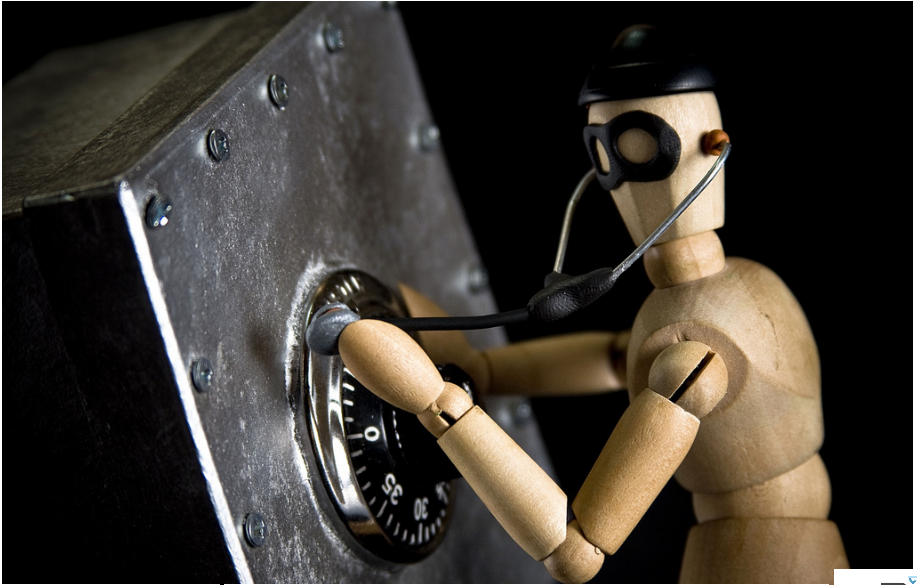
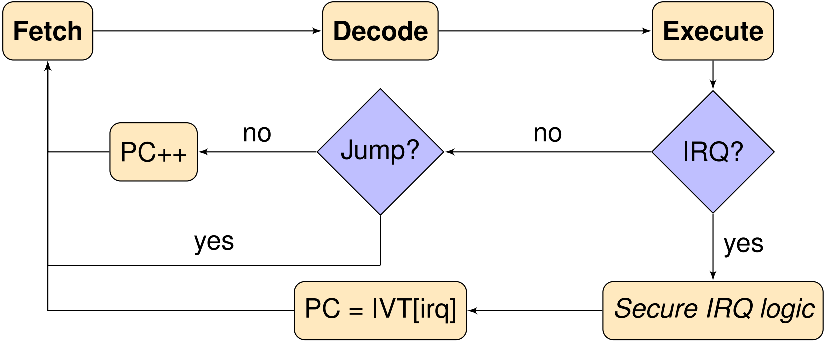
Untrusted OS → new class of powerful **side-channels**

Side-Channel Attack Principle

Side-Channel Attack Principle

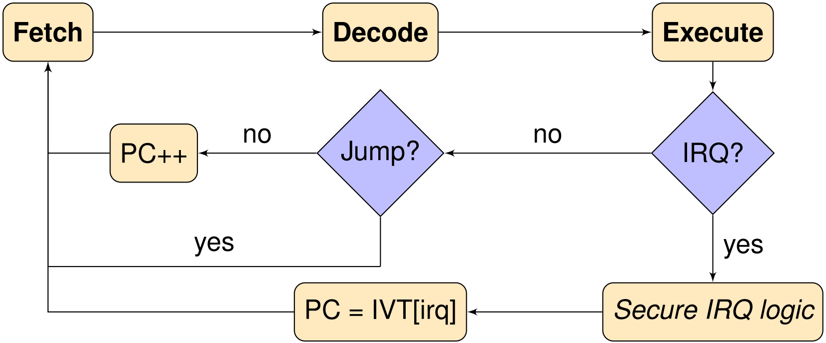


Fetch-Decode-Execute CPU Operation



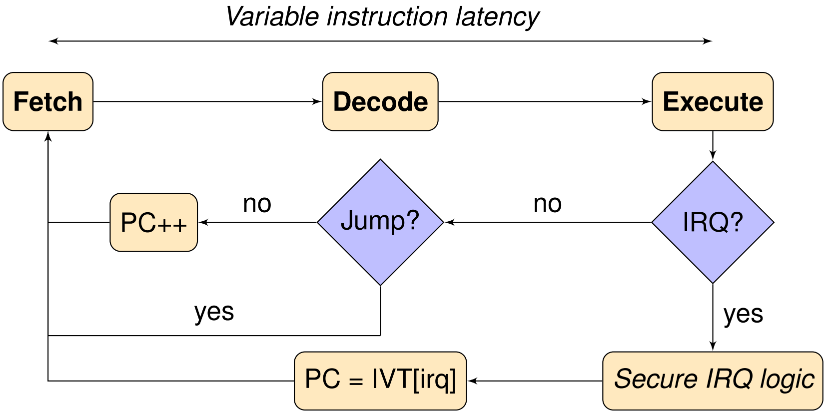
Fetch-Decode-Execute CPU Operation

Note: IRQ only served *after current instruction* has completed

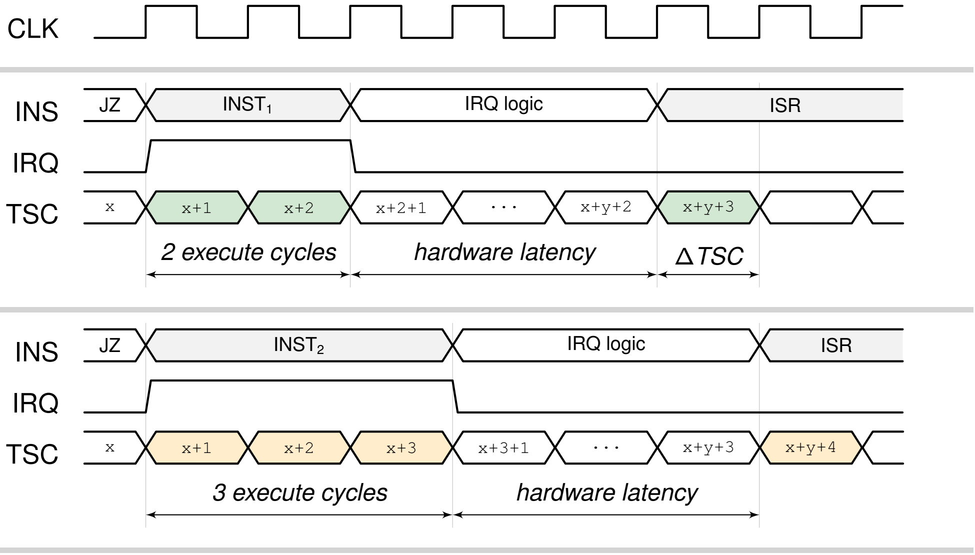


Wait a Cycle ...

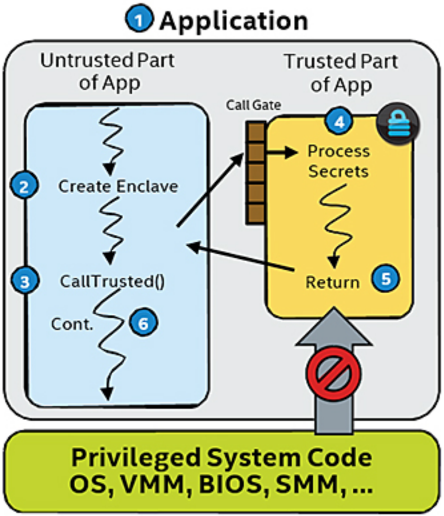
⇒ **IRQ latency leaks instruction execution time (!)**



Interrupt Latency as a Side-Channel



Intel SGX Helicopter View



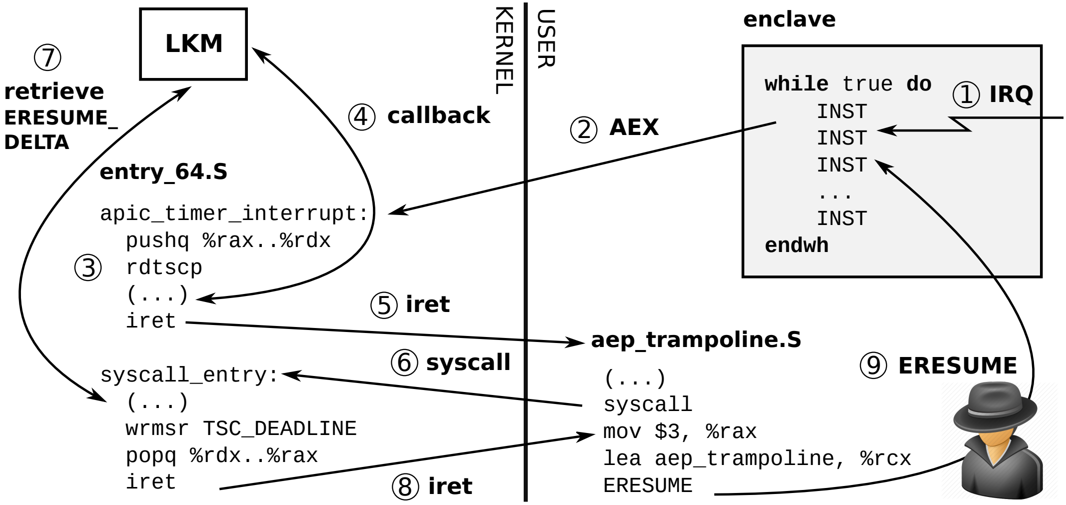
https://software.intel.com/en-us/sgx/details

- Protected enclave in application's **virtual address space**
- **x86** CPU: ∃ pipeline, cache, out-of-order execution, . . .
- Secure **interrupt** hardware mechanism: AEX/ERESUME

Interrupting and Resuming Enclaves

Goal: single-step through SGX enclave: interrupt each instruction sequentially and record corresponding *IRQ latency trace*

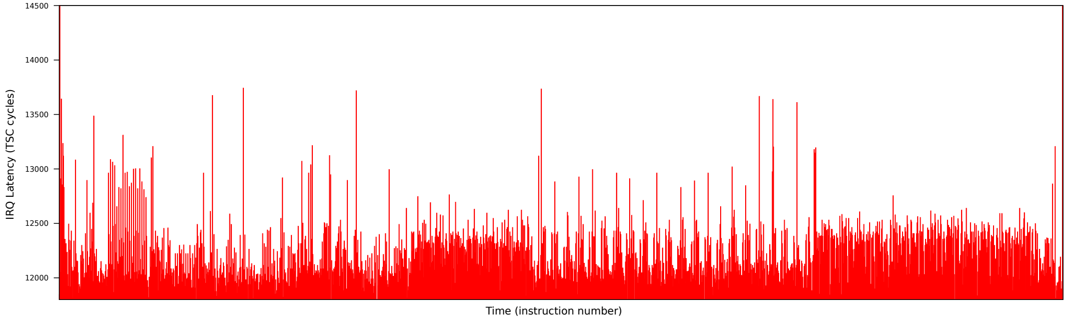
Interrupting and Resuming Enclaves



Macrobenchmark: Modular Exponentiation

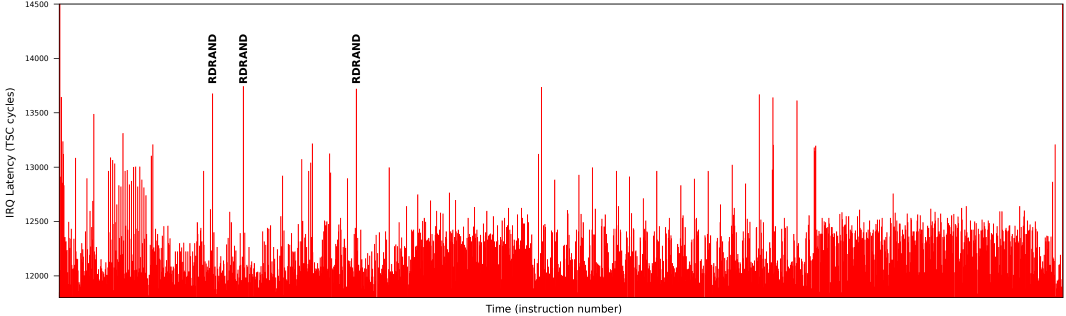
function SQUARE_AND_MULTIPLY(c,d,e,n)
    $r \leftarrow rand()$
    $c \leftarrow c * r^e \bmod n$
    $m \leftarrow 1$
    for most to least significant bit b in d **do**
        $m \leftarrow m^2 \bmod n$
        if b **then**
            $m \leftarrow m * c \bmod n$
        end if
    end for
    return $m * r^{-1} \bmod n$
end function

Extracted IRQ Latency Trace



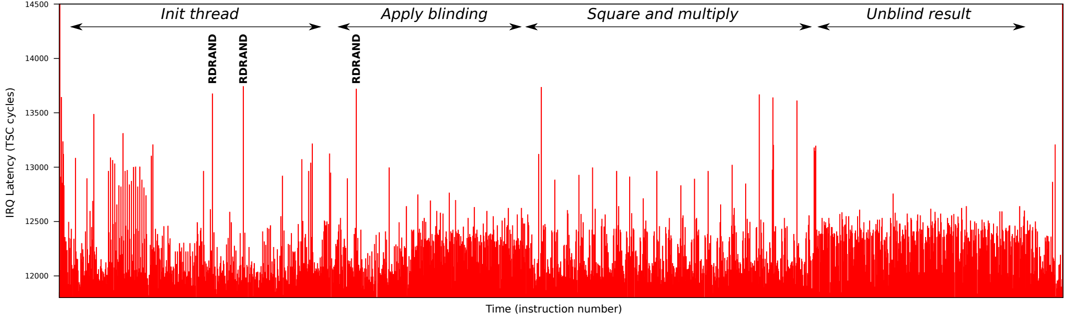
- “X-ray” extracted from a single **dummy RSA decryption**

Extracted IRQ Latency Trace



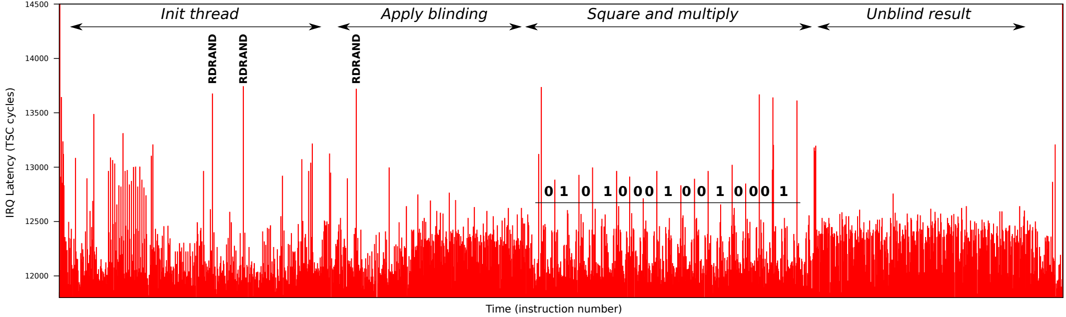
- "X-ray" extracted from a single **dummy RSA decryption**
- **Distinct instructions** for stack canary + blinding: RDRAND

Extracted IRQ Latency Trace



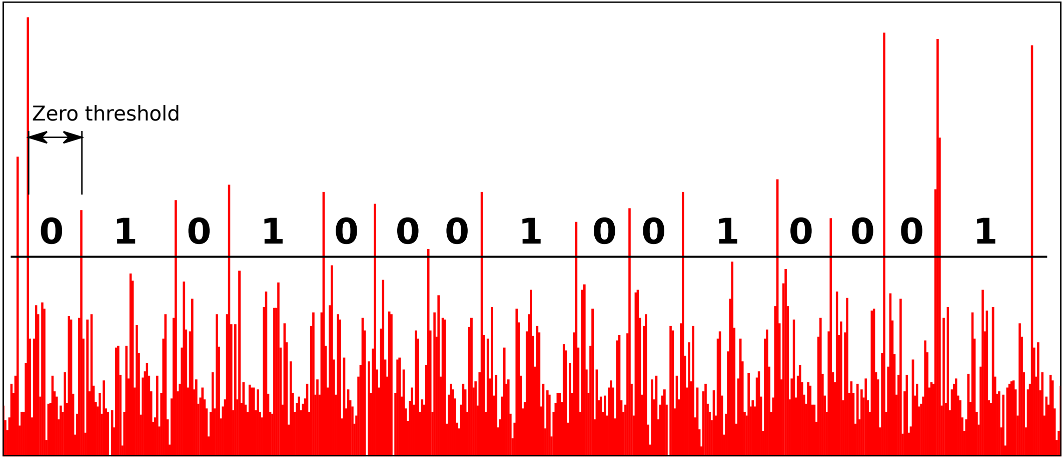
- “X-ray” extracted from a single **dummy RSA decryption**
- **Distinct instructions** for stack canary + blinding: RDRAND
- Sharply defined **algorithm phases**

Extracted IRQ Latency Trace



- "X-ray" extracted from a single **dummy RSA decryption**
- **Distinct instructions** for stack canary + blinding: RDRAND
- Sharply defined **algorithm phases**
- Full 16-bit **key recovery**

Extracted IRQ Latency Trace



Flush page table entry for *global variable accessed every loop iteration*

Side Channels: Be Aware!

Nemesis [VBPS18] is the first remote side-channel for **embedded + high-end** trusted computing hardware

IRQ latency trace reveals **micro-architectural** behaviour:

- Lots of *noise/non-determinism* on modern CPUs
- Abuse subtle timing differences with *machine learning*?

Defence techniques:

- Eliminate *secret-dependent control flow* $\leftrightarrow$ practice
- Sancus secure *hardware patch* to mask IRQ latency

Other Side Channels

Plenty of other software-controlled side-channel attack surface:

Caches: [GESM17] [vSMK^{+}21]

Page Faults: [WCP^{+}17]

Transient Out-of-Order Execution: [VBMW^{+}18]

Image Reconstruction. To reconstruct the Mona Lisa from the collected data sampled over multiple runs, we use our address selection capabilities to obtain all the candidates for every pixel address from our sampled data. Then we score each candidate based on the candidates for neighboring pixels using a distance function, selecting the candidate with the smallest score as the actual pixel value. The offline phase took 9s to reconstruct the image, which can be seen in Figure 10 (right).

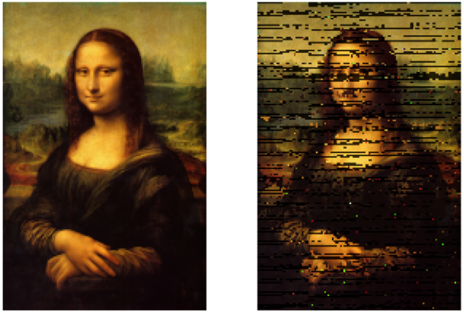


Fig. 10: On the left the original picture (128x194) and on the right the picture recovered from an SGX.

Image source: “CacheOut: Leaking data on Intel CPUs via cache evictions”, van Schaik et al., 2021. [vSMK^{+}21].

Summary

Trusted Execution Technology

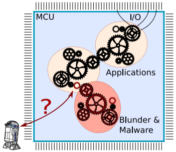
1. Strong application isolation and attestation
2. No protection against buggy software!
3. Potential for invasive use

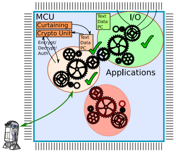
Sancus

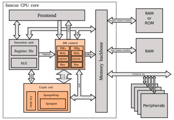
1. The Open-Source Trusted Computing Architecture
2. Built upon openMSP430 16-bit MCU, applications in IoT and embedded control systems
3. Research prototype under active development!

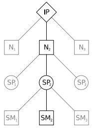
You still need: Threat Modeling, Testing, etc.

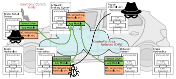
1. Understand what your assets are and what attackers you aim to protect against
2. Techniques to build really secure software
3. Use Trusted Computing to provide security in distributed scenarios and to protection against layer-below attacks!

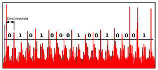












Thank you!

“The risks are about to get worse, because computers are being embedded into physical devices and will affect lives, not just our data.”

— Bruce Schneier, [Sch18]

Thank you! Questions?

https://distrinet.cs.kuleuven.be/
https://github.com/sancus-pma/tutorial-dsn18

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