Formally Secure Compartmentalizing Compilation

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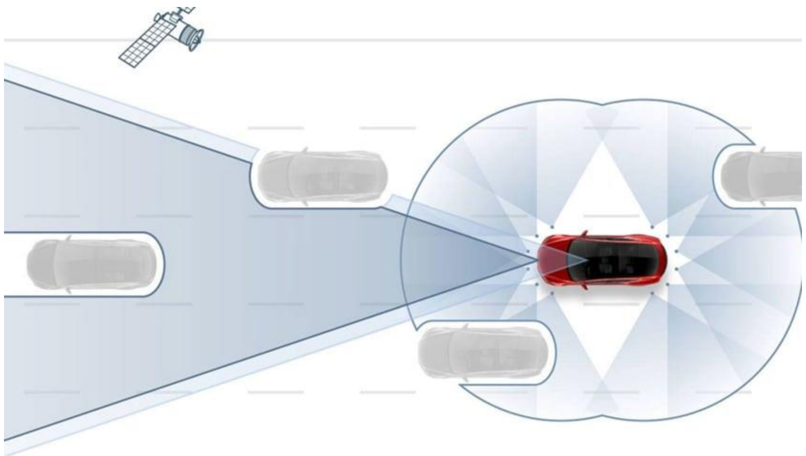
We are increasingly reliant on computers

... trusting them with our ~~digital~~ lives



Computers vulnerable to hacking

Windows 10 zero-day exploit code released online

Security researcher 'SandboxEscaper' returns with new Windows LPE zero-day.

By Catalin Cimpanu for Zero Day | May 22,

Heartbleed vulnerability may have been exploited months before patch [Updated]

Fewer servers now vulnerable, but the potential damage rises.

GOOGLE \ TECH \ ANDROID

21

Google finds Android zero day that can take control of Pixel and Galaxy devices

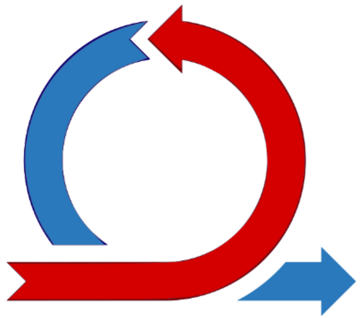
Affecting devices from Samsung, Huawei, and Google itself

By Jon Porter | @JonPorty | Oct 4, 2019, 8:42am EDT

SHARE

Hackers Remotely Kill a Jeep on the Highway—With Me in It

Need to break the exploitation cycle

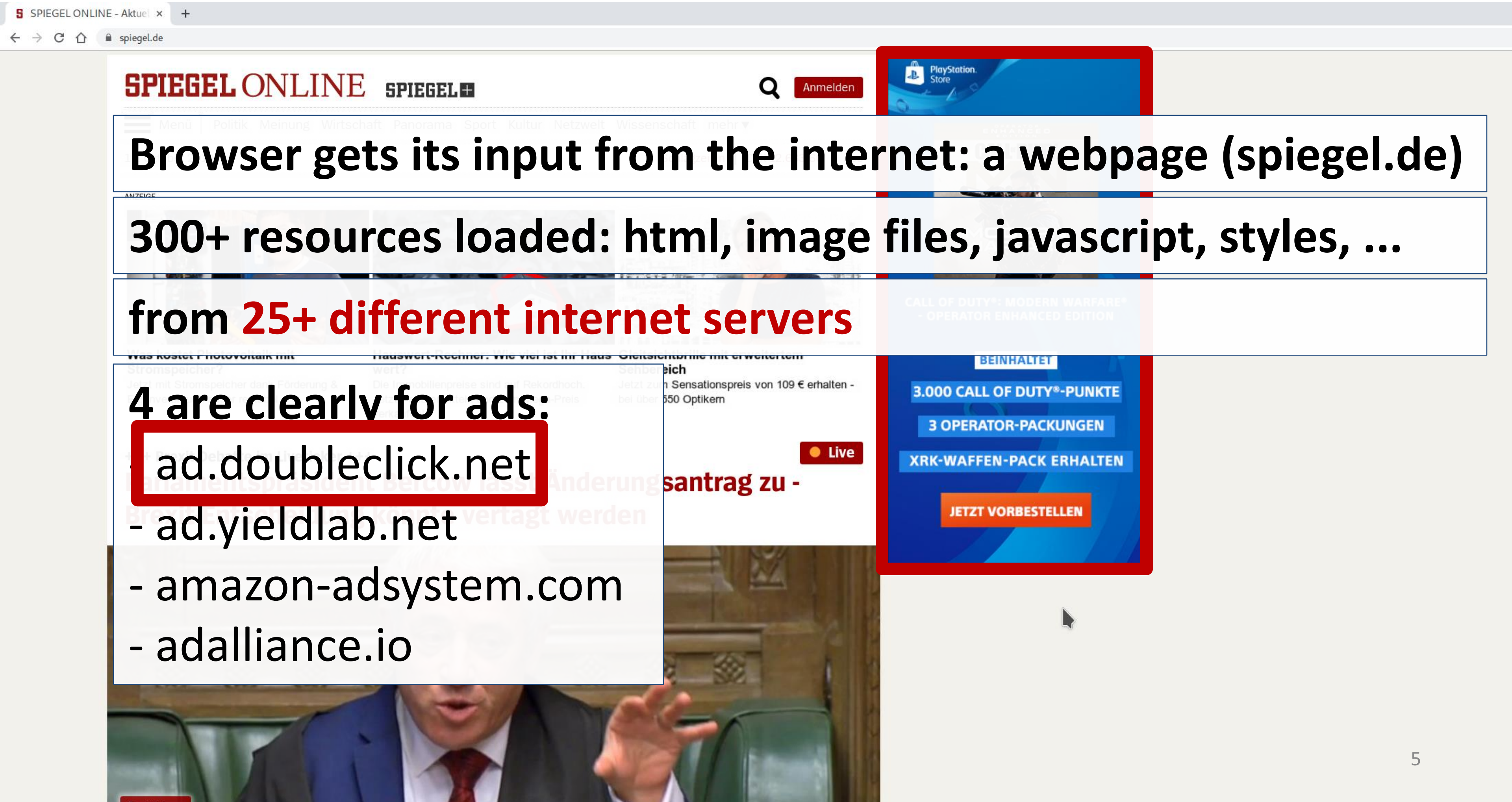


- Once the stakes are high enough, **attackers will find a way to exploit *any* vulnerability**
- **Weak security defenses** get deployed,

We need a deeper understanding that we can use to build provably secure defenses

-
  - defenders find clever ways to "increase attacker effort"
  - **attackers find clever ways around them**

Web browsers are frequently hacked



Browser gets its input from the internet: a webpage (spiegel.de)

300+ resources loaded: html, image files, javascript, styles, ...

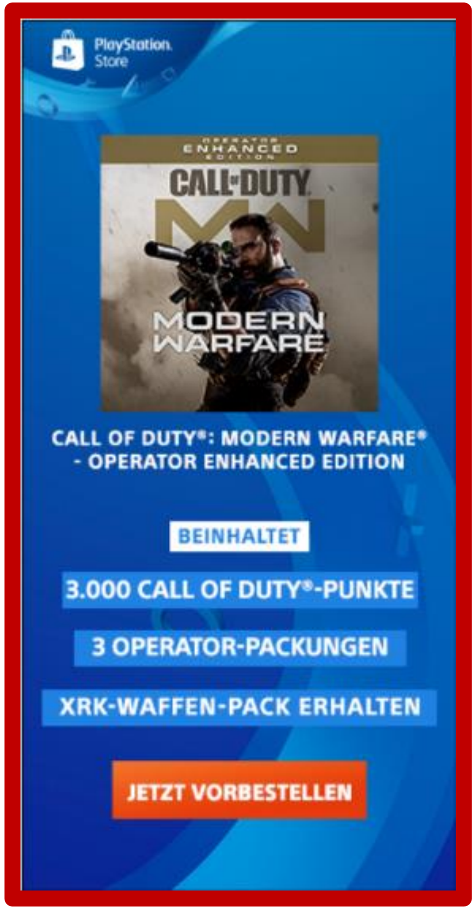
from 25+ different internet servers

4 are clearly for ads:

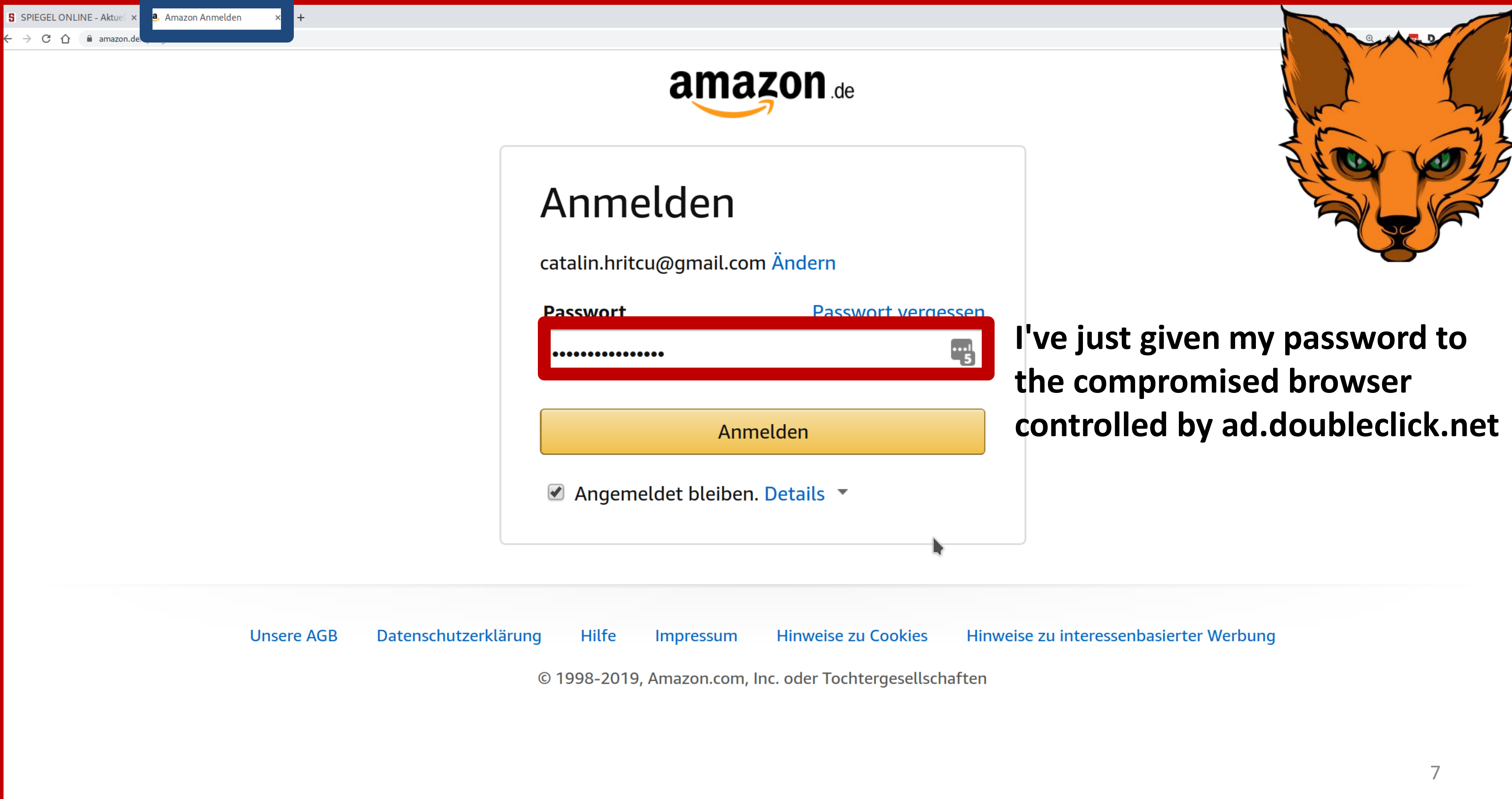
- ad.doubleclick.net
- ad.yieldlab.net
- amazon-adsystem.com
- adalliance.io

Malicious server can hack the browser

- send it an image that **looks like an** ad
- **specially crafted to exploit a vulnerability** in the browser's image drawing engine
- **this compromises the whole browser**
  - i.e. gives server **complete control** over it
- **malicious server can now:**
  - steal the user's data
  - take control of the victim's computer
  - encrypt victim's data and ask for ransom

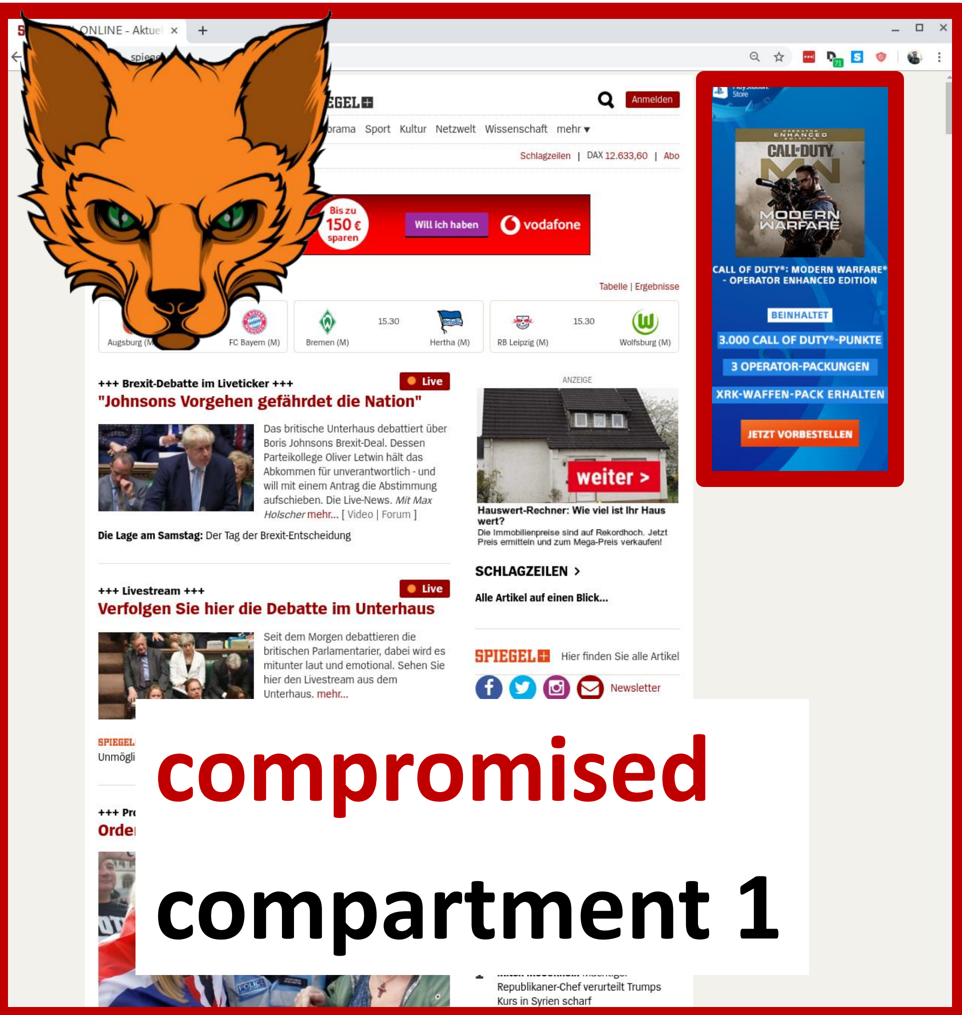


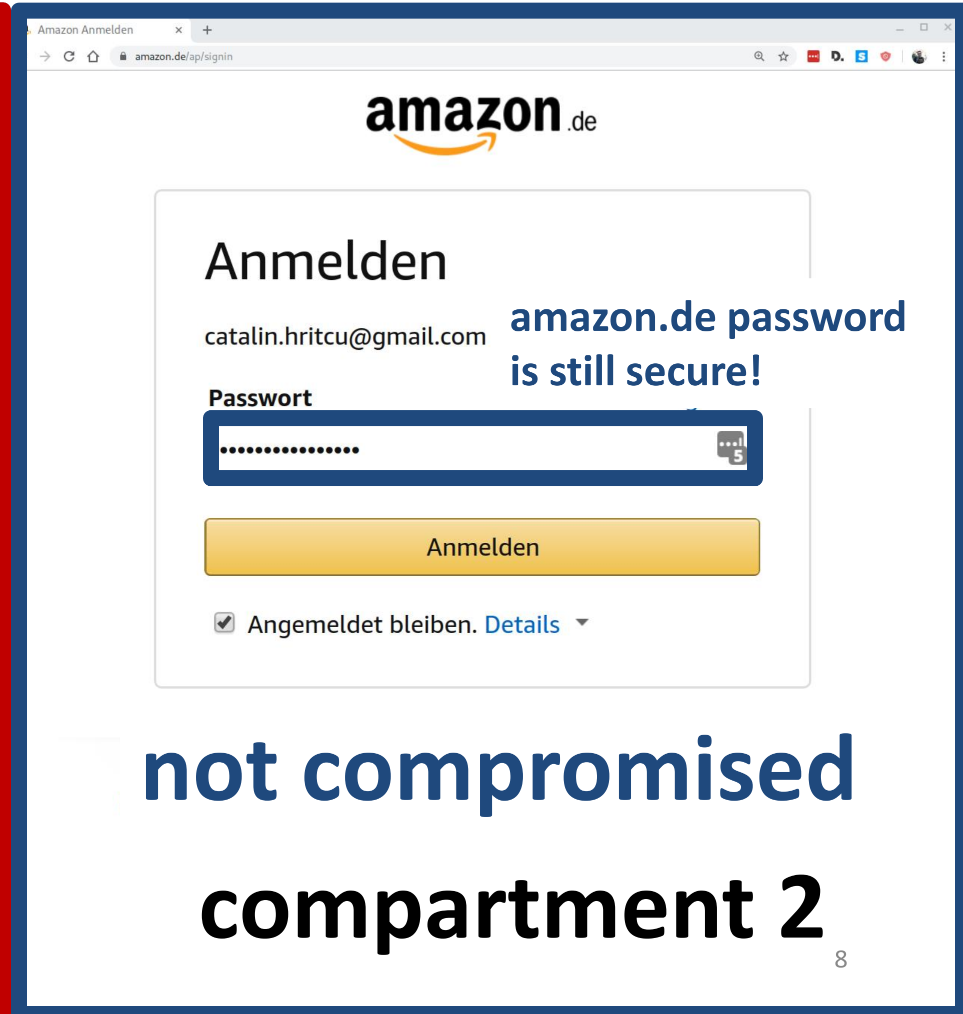
Compromised browser can steal user's data



I've just given my password to the compromised browser controlled by ad.doubleclick.net

Compartmentalization can help





Good news: browsers now compartmentalized!

- **each tab indeed started in separate compartment**

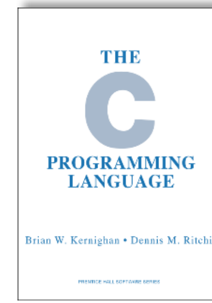
Bad news, so far:

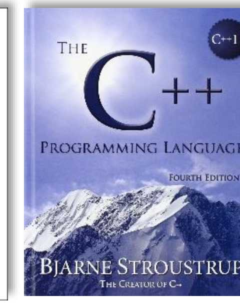
- **limited compartmentalization mechanism**
  - **compartments coarse-grained**
    - can compartmentalize tabs, but not secrets within a tab
  - **compartments can't naturally interact**
    - even for tabs this required big restructuring of web browsers

Fine-grained compartmentalization

Fine-grained compartmentalization

Source language compartments





- Mozilla Firefox mostly implemented in C/C++
- Programming languages like C/C++, Java, F*, ... already provide **natural abstractions** for **fine-grained compartmentalization**:
  - procedures, interfaces, classes, objects, modules, libraries, ...
  - a **compartment** can be a library/module/class or even an object (e.g., an image)
- **In the source language fine-grained compartments are easy to define** and **can naturally interact**

Source language compartments

```
compartment C1 {
  private var x;

  private procedure p() {
    x := get_counter();
    x := password; ←not allowed
  }
}
```

```
compartment C2 {
  private var counter;
  private var password;

  public procedure get_counter() {
    counter := counter + 1;
    return counter;
  }
}
```

Abstractions lost during compilation

- **Computers don't run C/C++, Java, or F***
  - **Compiler** translates Firefox **from C/C++ to machine code instructions**
- **All compartmentalization abstractions lost during compilation**
  - no procedures, no interfaces, no classes, no objects, no modules, ...
- **Secure compilation**
  - **preserve abstractions through compilation, enforce them all the way down**
- **Shared responsibility of the whole compilation chain:**
  - source language, compiler, operating system, and hardware
- **Goal: secure compartmentalizing compilation chain**

Machine-code level

Compartment C_1

<<check rx$\in C_1$>>

load r $\leftarrow$ [rx]

$\leftarrow$not allowed

put rc $\leftarrow$ $a_{password}$

<<check rx$\in C_1$

or rx$\in C_2$'s interface>>

jump-and-link rx

$\leftarrow$not allowed

sub r $\leftarrow$ r-1

Compartment C_2

put rc $\leftarrow$ $a_{counter}$

load r $\leftarrow$ [rc]

add r $\leftarrow$ r+1

store r $\rightarrow$ [rc]

jump ra

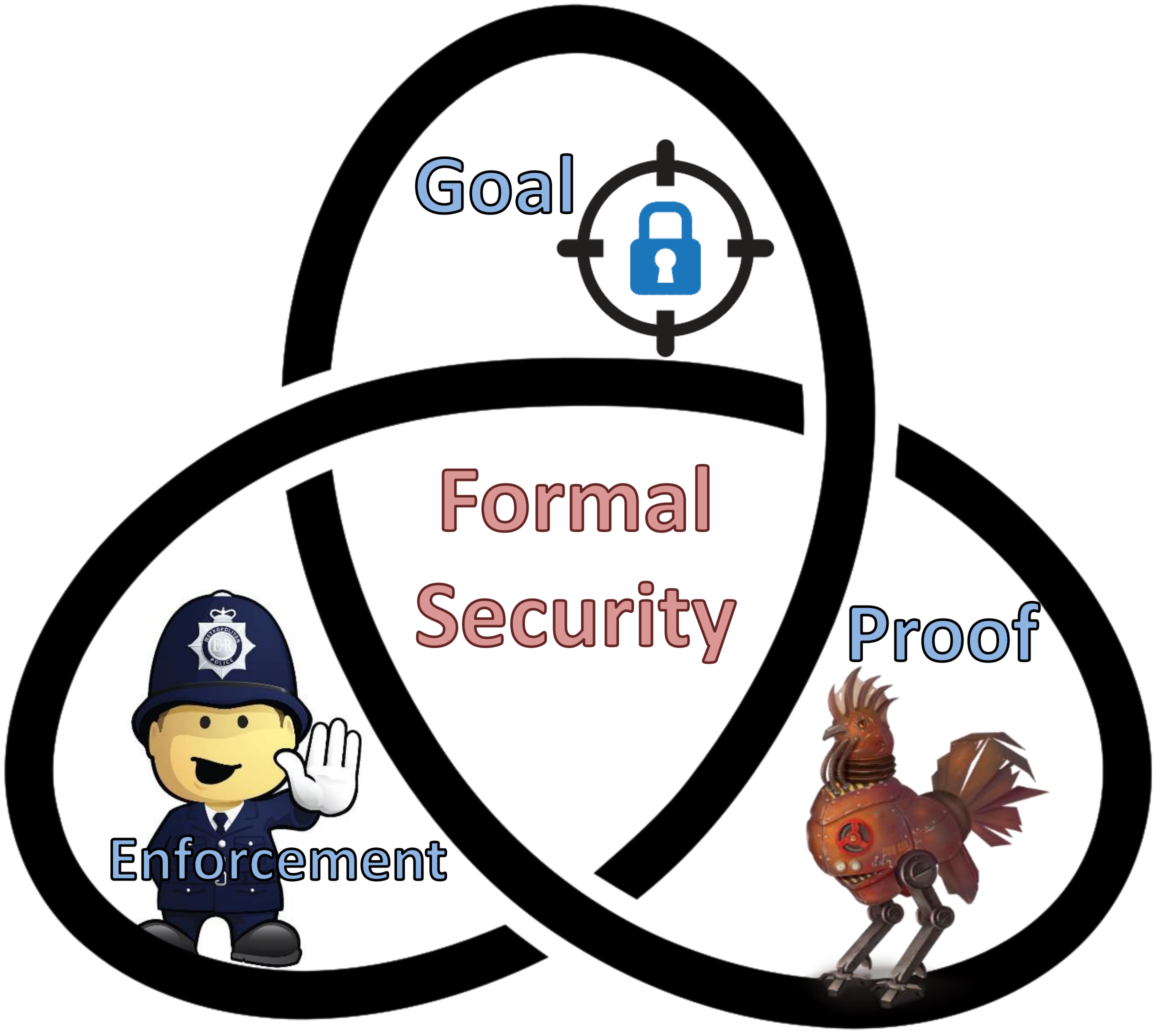
compiled get_counter (public procedure)

$a_{counter}$: 42

$a_{password}$: …

Securely enforcing source abstractions is challenging!

Formally Secure Compartmentalizing Compilation



1. Security Goal

- **What does it mean for a compartmentalizing compilation chain to be secure?**
  - **formal definition expressing end-to-end security guarantees**
  - **these guarantees were not understood before**
- **Will start with an easier definition**
  - **protecting a 1 trusted compartment from 1 untrusted one**
  - **untrusted compartment arbitrary** (e.g. compromised Firefox)
  - **trusted compartment has no vulnerabilities**

This is not just hypothetical!

Firefox

Mozilla shipping EverCrypt verified crypto library

(also used by Microsoft, Linux, ...)

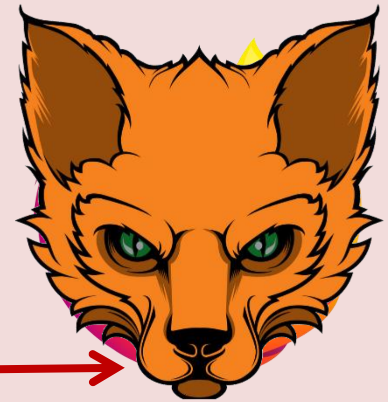
[POPL'16,'17,'18,'20, ICFP'17,'19, ESOP'19, CPP'18, SNAPL'17]

Formal verification milestone:

40.000+ lines of highly-efficient code, mathematically proved to be free of vulnerabilities

(and functionally correct and side-channel resistant)

Putting things into perspective



EverCrypt
(verified in F*)

Firefox

40.000 lines

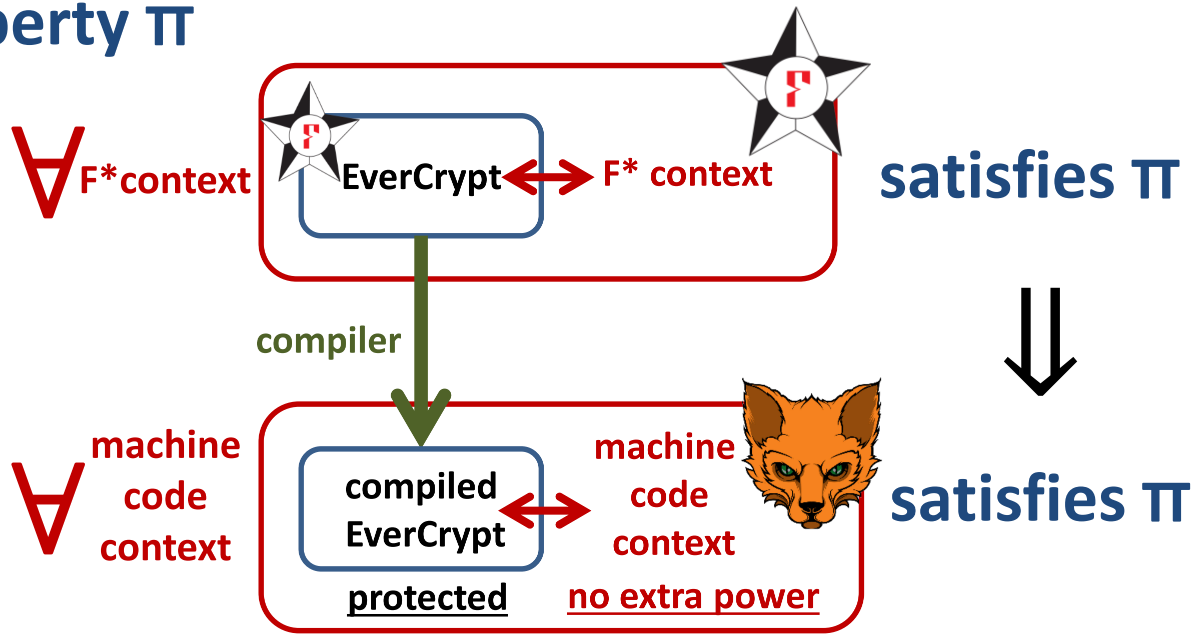
20.000.000 lines
+ external libraries
all unverified

Without compartmentalization interoperability is insecure:
if Firefox is compromised it can break security of verified code

What does secure compartmentalization mean in this setting?

Preserving security against adversarial contexts

∀ security property π



Where "security property" can e.g., be
safety or integrity or confidentiality [CSF'19]

π = "EverCrypt's private key is not leaked"

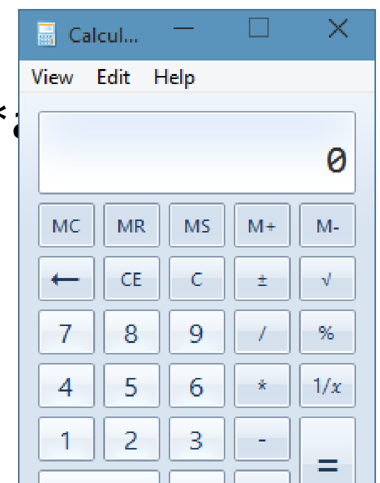
Extra challenges for our real security definition [CSF'16, CCS'18]

- Program split into **many mutually distrustful compartments**
- **We don't know which compartments will be compromised**
  - **every compartment should be protected from all the others**
- **We don't know when a compartment will be compromised**
  - **every compartment should receive protection until compromised**

Formalizing security of mitigations is hard

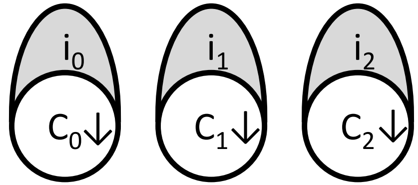
- **We want source-level security reasoning principles**
  - easier to **reason about security in the source language** if and application is compartmentalized
- **... even in the presence of undefined behavior**
  - can't be expressed at all by source language semantics!
  - **what does the following program do?**

```
#include <string.h>
int main (int argc, char **
    char c[12];
    strcpy(c, argv[1]);
    return 0;
}
```



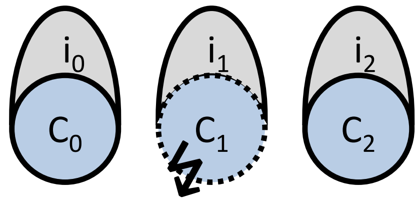
Compartmentalizing compilation should ...

- **Restrict spatial scope** of undefined behavior
  - **mutually-distrustful components**
    - **each component protected from all the others**
- **Restrict temporal scope** of undefined behavior
  - **dynamic compromise**
    - **each component gets guarantees as long as it has not encountered undefined behavior**
    - i.e. the mere existence of vulnerabilities doesn't necessarily make a component compromised

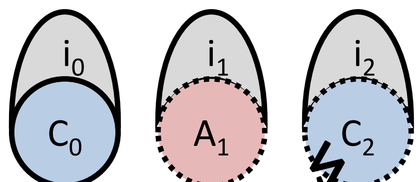
Security definition: If 

$\rightsquigarrow_{\text{machine}}$ m then

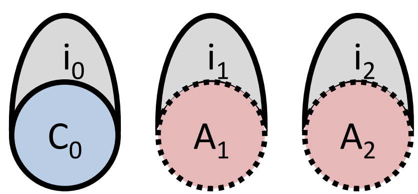
$\exists$ a sequence of component compromises explaining the finite trace m in the source language, for instance $m{=}m_1{\cdot}m_2{\cdot}m_3$ and

(1) 

$\rightsquigarrow_{\text{source}}$ $m_1\cdot\text{Undef}(C_1)$

(2) $\exists A_1$. 

$\rightsquigarrow_{\text{source}}$ $m_1\cdot m_2\cdot\text{Undef}(C_2)$

(3) $\exists A_2$. 

$\rightsquigarrow_{\text{source}}$ $m_1\cdot m_2\cdot m_3$

Finite trace *m* records which component encountered undefined behavior and allows us to rewind execution

2. Security Enforcement

Prototype compartmentalizing compilation chain

```
compartment C2 {
  private var counter;
  private var password;
  public procedure get_counter() {
    counter := counter + 1;
    return counter;
  }
}
```

Compartmentalized source language

Buffers, procedures, **compartments**

Compartmentalized intermediate language

Intermediate language with **built-in compartmentalization**

new

Programmable tagged architecture

Bare-bone machine

Machine code

Hardware-accelerated enforcement

[POPL'14, Oakland'15, ASPLOS'15, POST'18, CCS'18]

+Software enforcement

Software-fault isolation

Compartment C_1

<<check rx∈C_1>>

load r ← [rx]

put rc ← $a_{password}$

<<check rx∈C_1 ←not enough

or rx∈C_2's interface>>

jump-and-link rx

sub r ← r-1

Compartment C_2

a_1: put rc ← $a_{counter}$

a_2: load r ← [rc]

a_3: add r ← r+1

a_4: store r → [rc]

a_5: jump ra

$a_{counter}$: 42

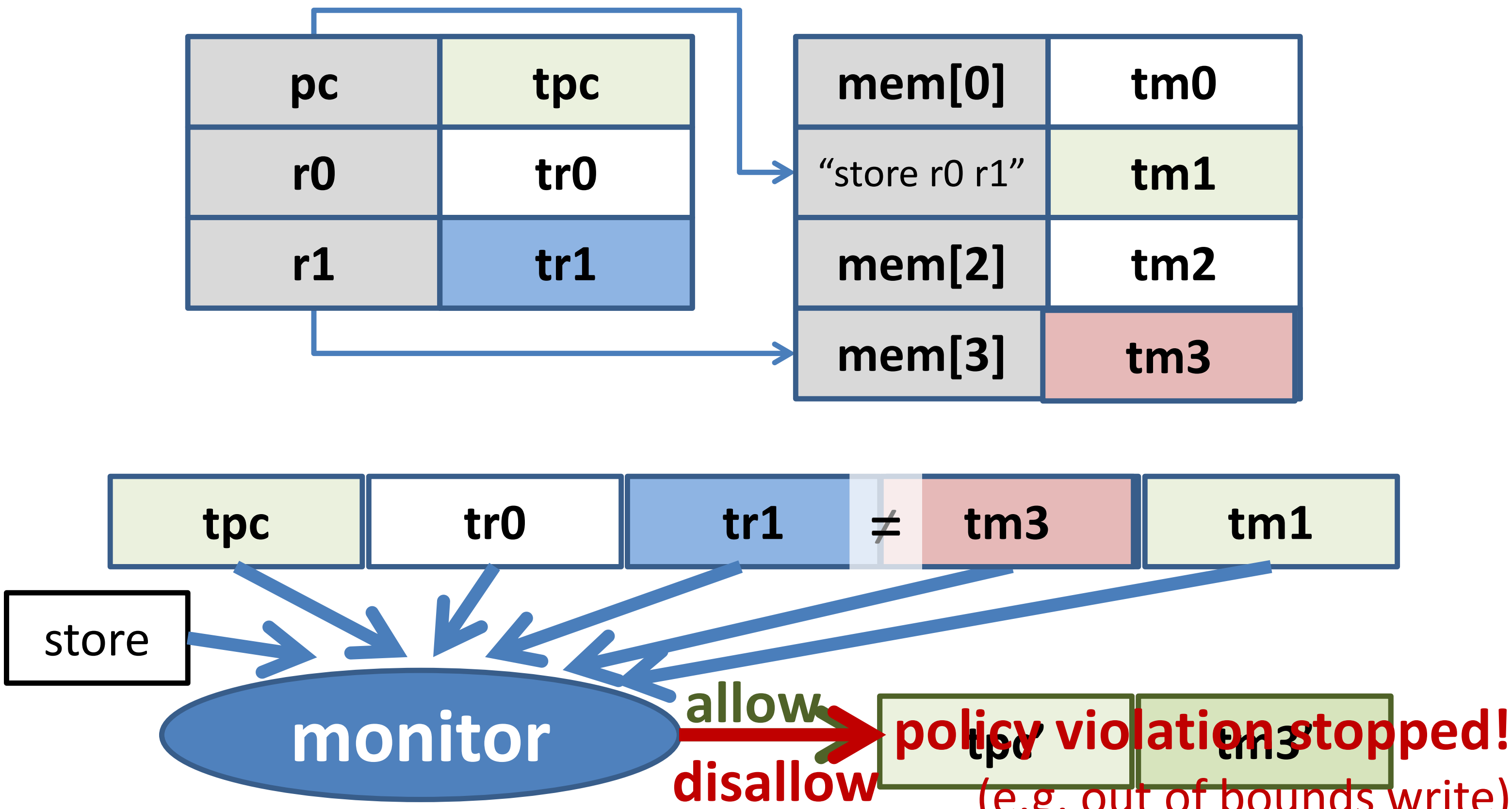
$a_{password}$: …

Idea: rewrite C_1's (& C_2's) code to insert all the required checks

Challenges: checks complicated (uncircumventable, efficient)

Micro-Policies [POPL'14, Oakland'15, ASPLOS'15, POST'18, CCS'18]

software-defined, hardware-accelerated, tag-based monitoring



software monitor’s decision is hardware cached

Compartmentalization micro-policy

Compartment C_1

load r ← [rx]

not allowed

put rc ← $a_{password}$

pc@C_1

jump-and-link rx

sub r ← r-1 @NoEntry

Compartment C_2

a_1: put rc ← $a_{counter}$ @EntryPoint

a_2: load r ← [rc] $\boxed{\text{@NoEntry}}$

a_3: add r ← r+1 @NoEntry

a_4: store r → [rc] @ ...

a_5: jump ra pc@C_2

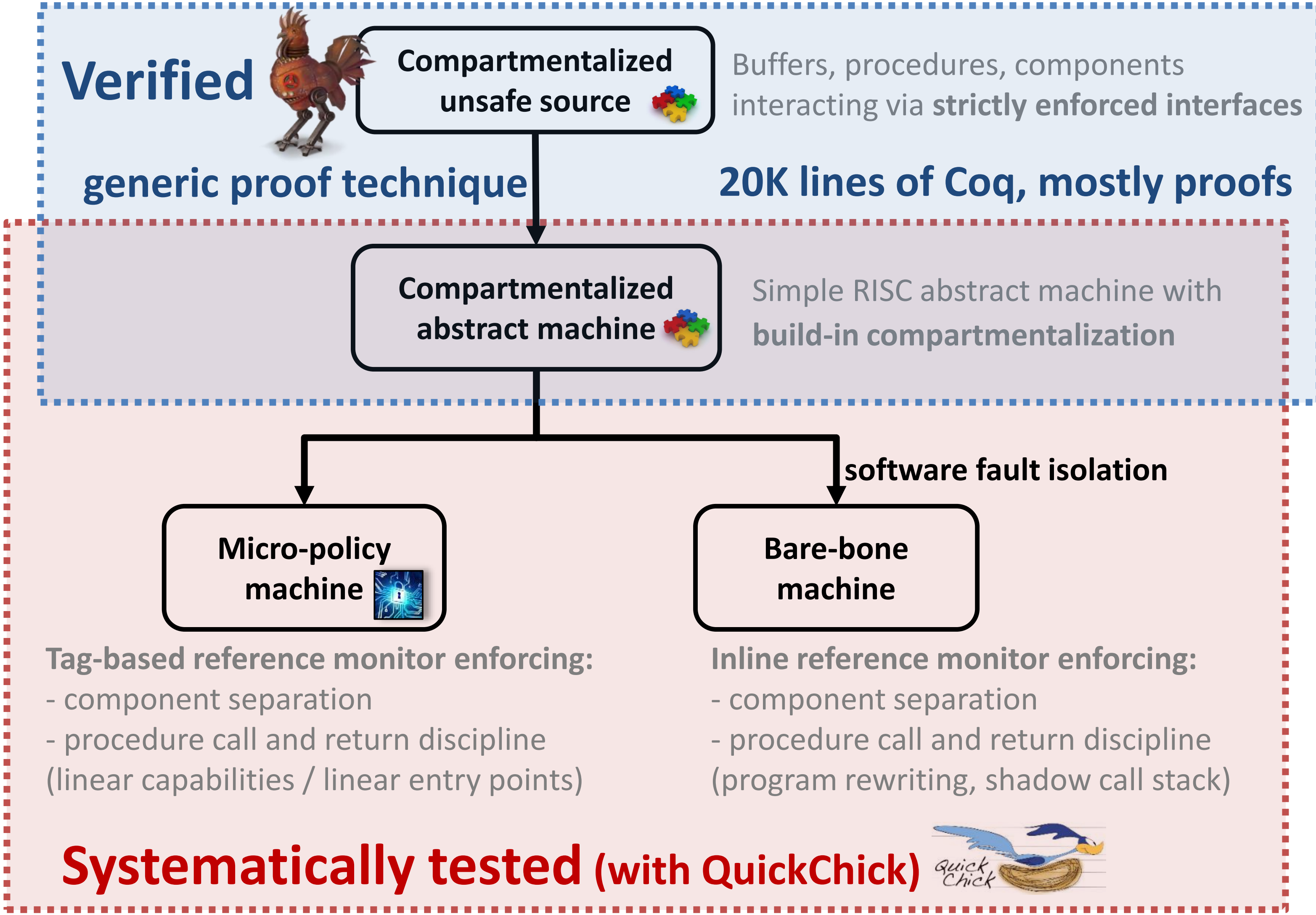
$a_{counter}$: 42

$a_{password}$: ...

Challenge: making sure returns go to the right place

3. Security Proof

- **Proving mathematically that a compartmentalizing compilation chain achieves the security goal**
  - formally verifying the security of the whole compilation chain
  - such proofs **very difficult and tedious**
    - wrong conjectures survived for decades; 250pg for toy compiler
  - we propose a **more scalable proof technique**
  - focus on **machine-checked proofs** in the Coq proof assistant
  - **Proof-of-concept formally secure compilation chain in Coq**



https://secure-compilation.github.io

Summary

Compartmentalizing compilation is an important security defense in practice

1. Goal: formalize end-to-end security guarantees

– first definition supporting **mutually distrustful components** and **dynamic compromise**

2. Enforcement: protect abstractions all the way down

– **software fault isolation** or **tag-based architecture**

3. Proof: verify security of entire compilation chain

– **scalable proof technique machine-checked in Coq**

Making this **more practical** ... next steps:

- **Scale formally secure compilation chain to C language**
  - allow **pointer passing** (capabilities for fine-grained memory sharing)
  - eventually support enough of C to **measure and lower overhead**
  - check whether hardware support (tagged architecture) is faster
- **Extend all this to dynamic component creation**
  - rewind to when compromised component was created
- **... and dynamic privileges**
  - capabilities, dynamic interfaces, history-based access control, ...
- **From robust safety to hypersafety (confidentiality) [CSF'19]**
- **Secure compilation of EverCrypt, miTLS, ...**

My dream: secure compilation at scale

language

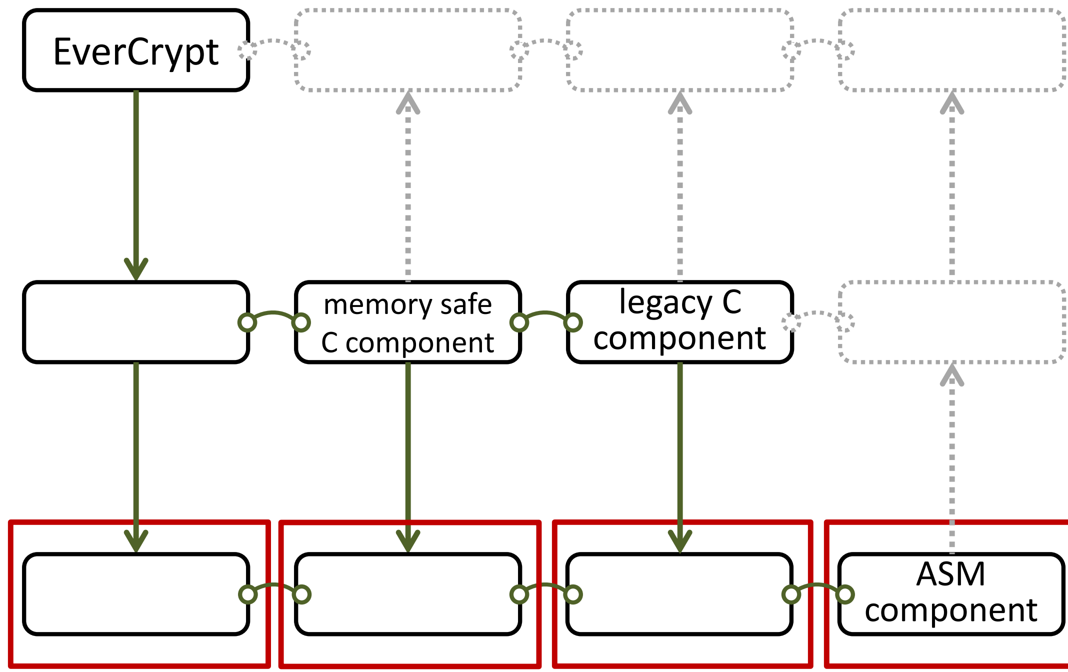
C language

+ components

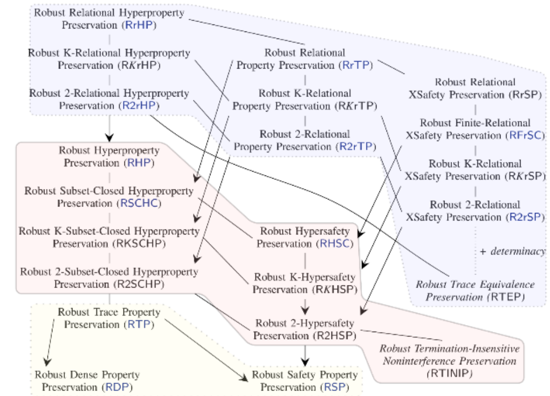
+ memory safety

ASM language

(RISC-V + micro-policies)



Going beyond Robust Preservation of Safety



Journey Beyond Full Abstraction (CSF 2019)

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Marco Patrignani
Stanford & CISPA

Going beyond Robust Preservation of Safety [CSF'19]

relational hyperproperties (trace equivalence)

+ code confidentiality

hyperproperties (noninterference)

+ data confidentiality

trace properties (safety & liveness)

only integrity

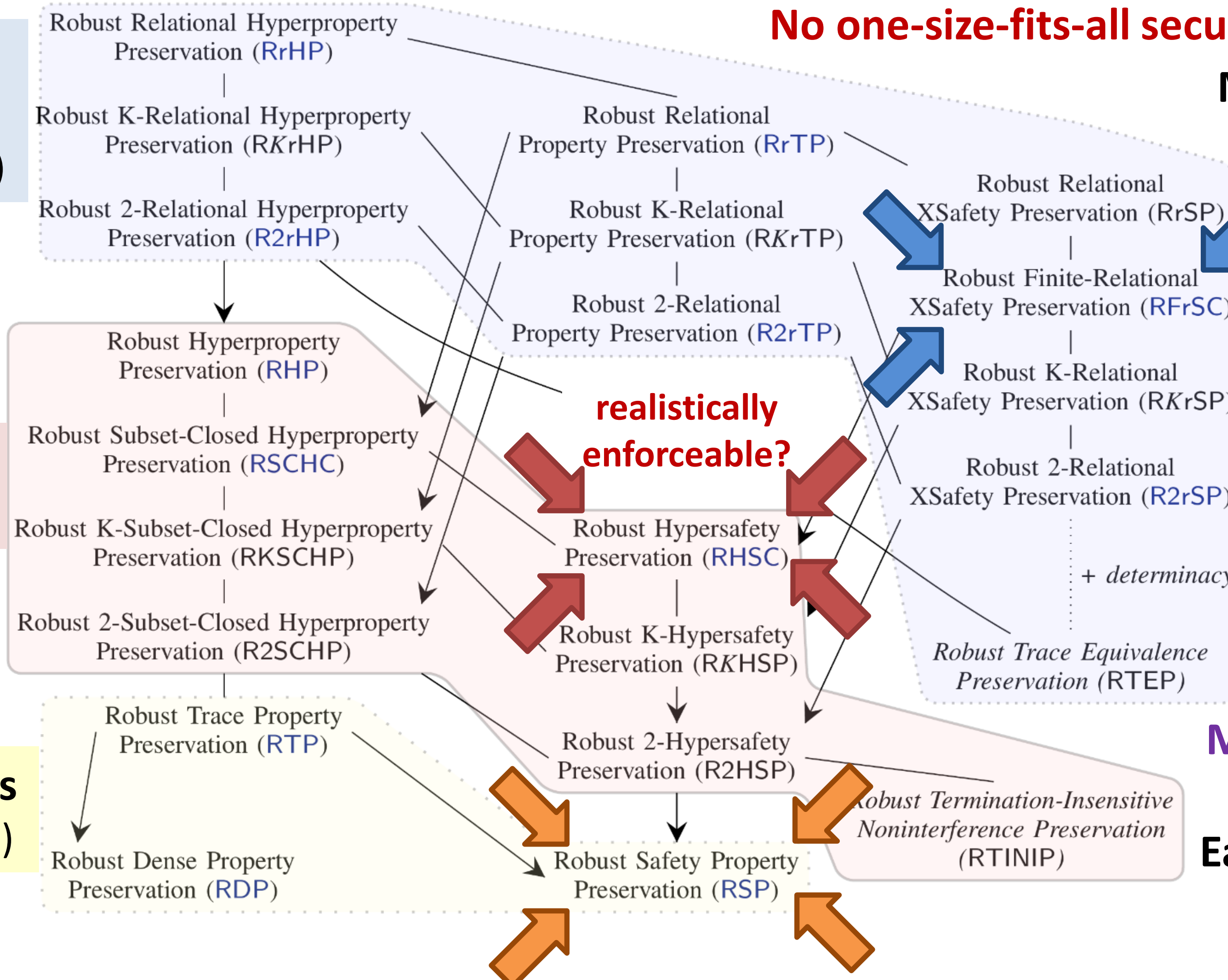
No one-size-fits-all security criterion

More secure

current proof technique

More efficient to enforce

Easier to prove



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3. Proof: verify security of entire compilation chain

– **scalable proof technique machine-checked in Coq**