# Formally Secure Compartmentalizing Compilation

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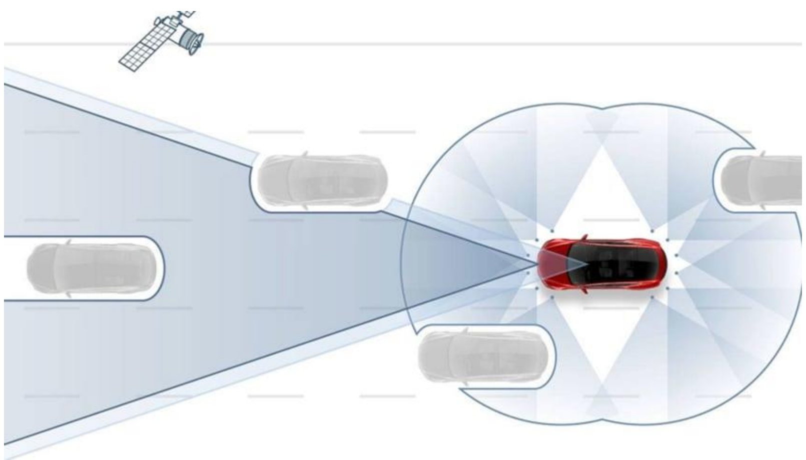
# We are increasingly reliant on computers


# ... 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

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

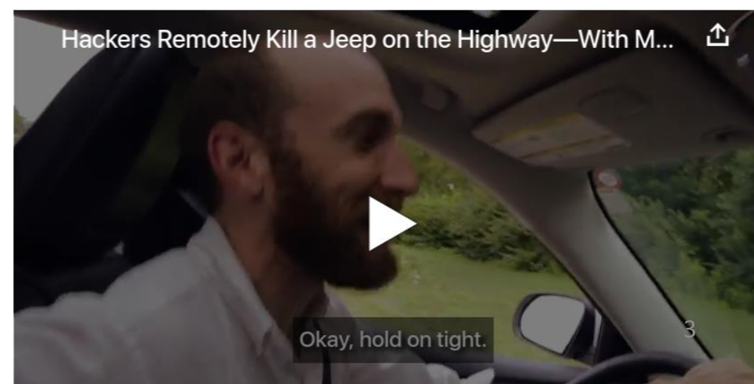
21

*Affecting devices from Samsung, Huawei, and Google itself*

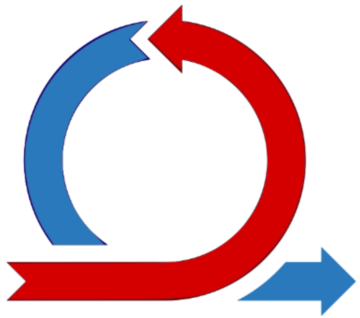
By Jon Porter | @JonPorty | Oct 4, 2019, 8:42am EDT

SHARE

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



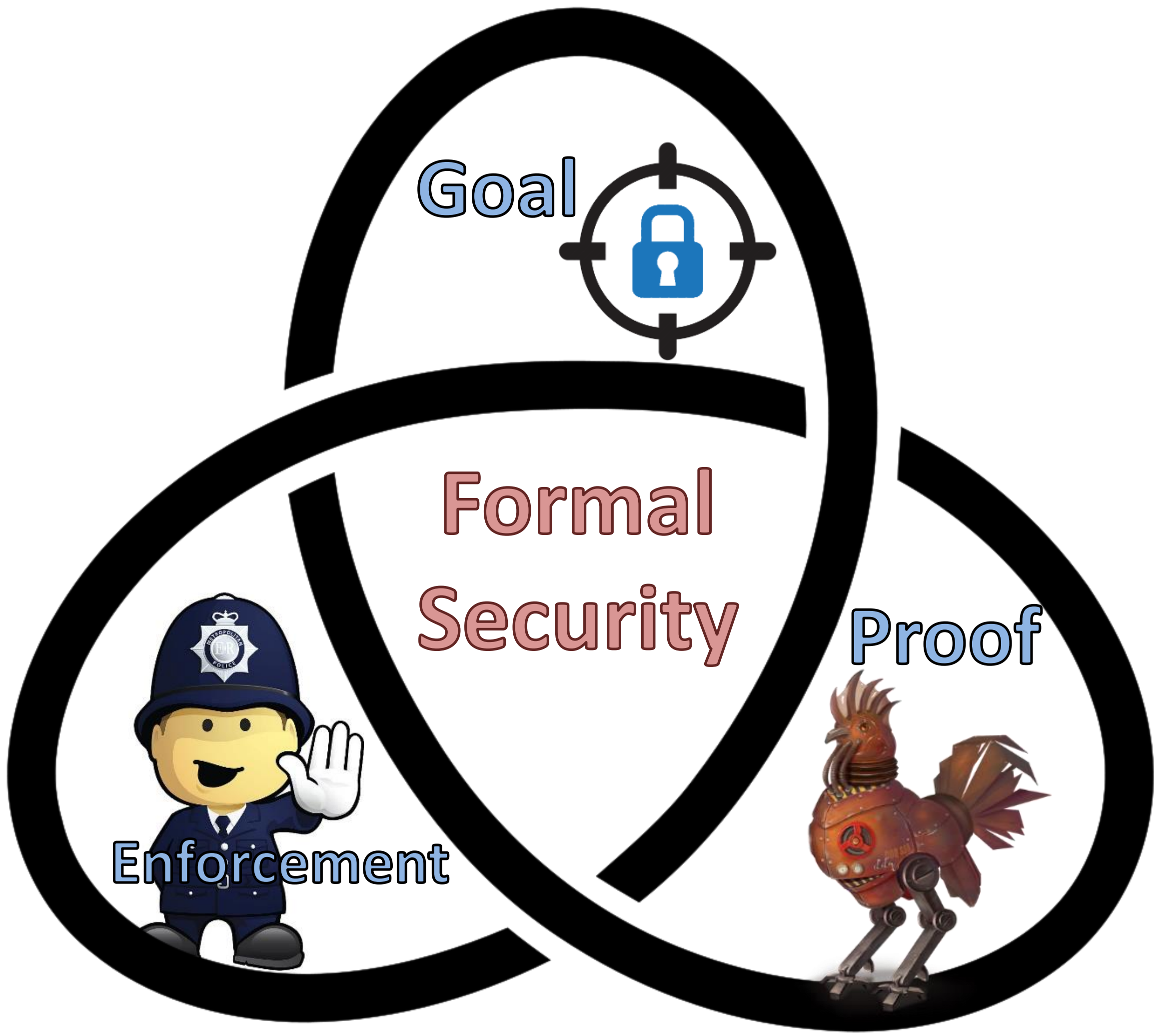
# Need to break the exploitation cycle



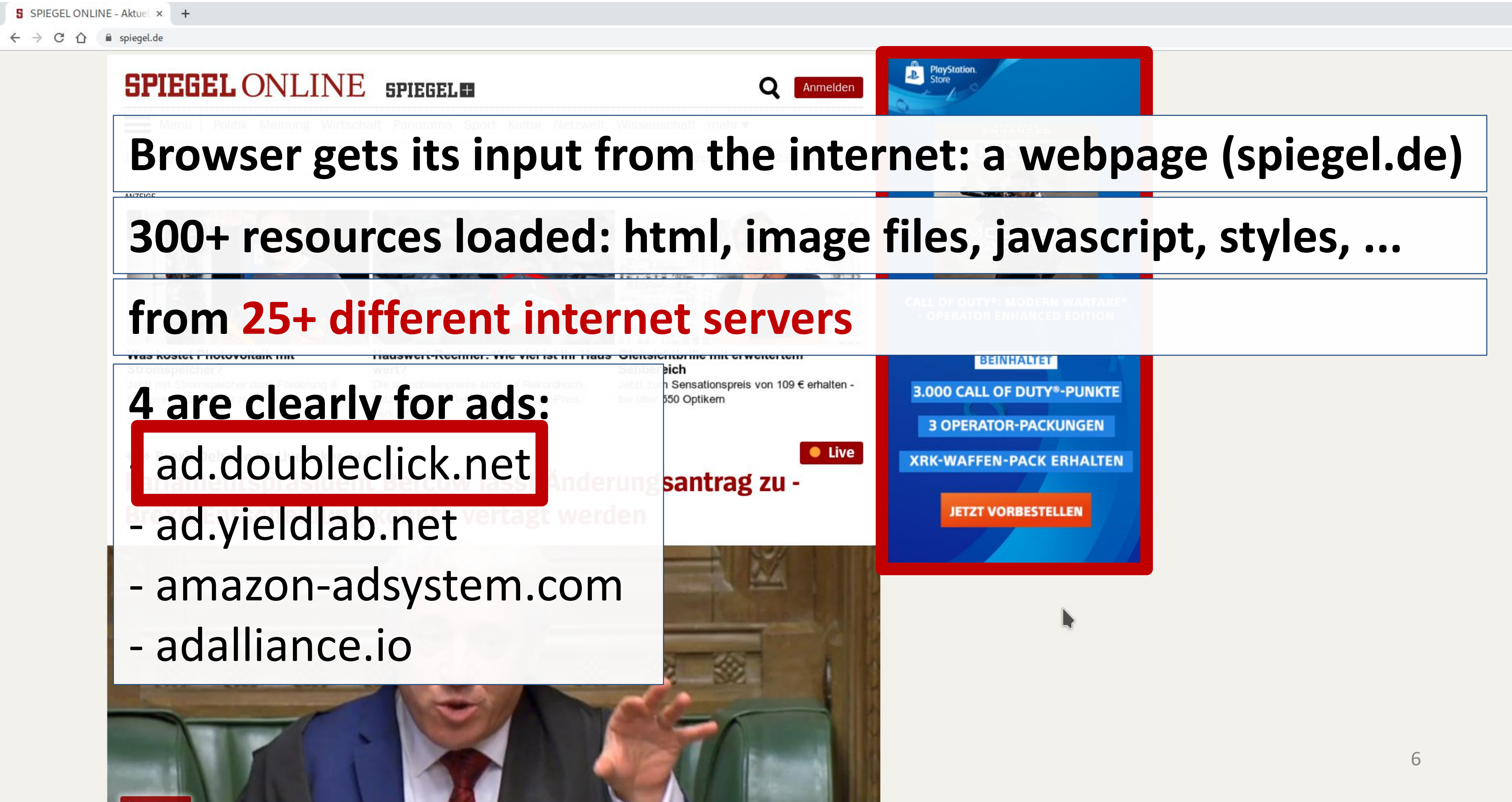
- Once the stakes are high enough, **attackers will find a way to exploit *any* vulnerability**
- **Weak security defenses** get deployed,

**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**


Goal
Formal
Security
Proof
Enforcement

# 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**

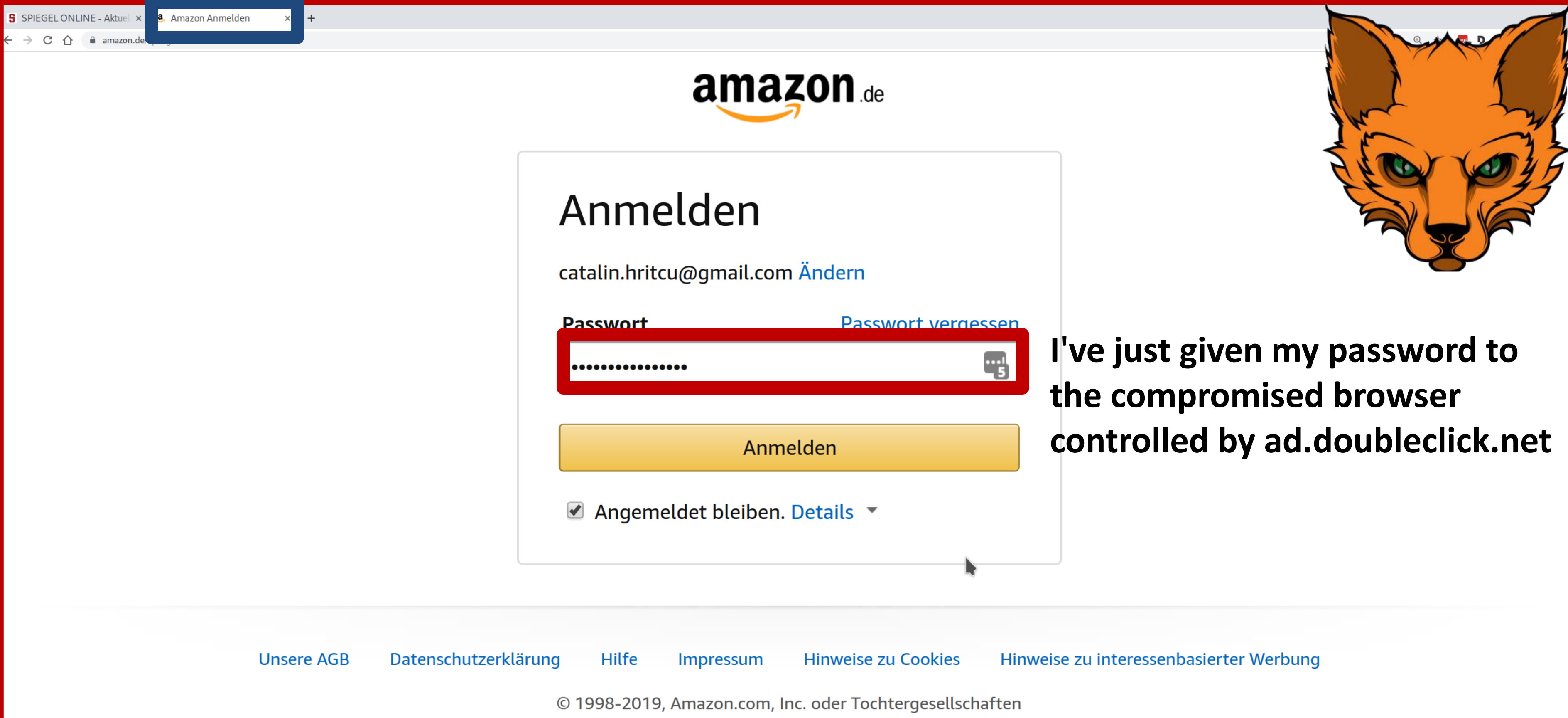
**4 are clearly for ads:**

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

# Malicious server can hack the browser

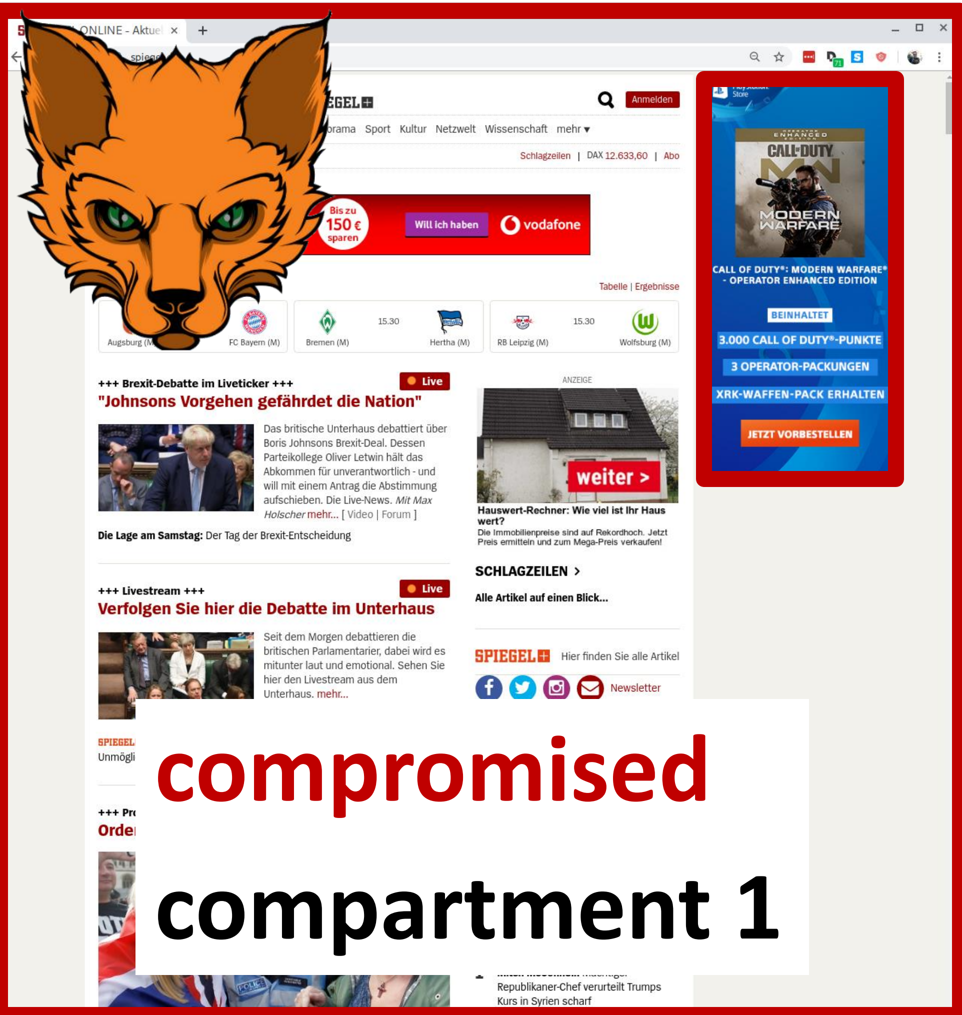
- send it an image that **looks like an** ad
- **specially crafted to exploit a vulnerability** in the browser's image drawing engine
- **this compromises the whole browser**
  - i.e. gives server **complete control** over it
- **malicious server can now:**
  - steal the user's data
  - take control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

# Compromised browser can steal user's data



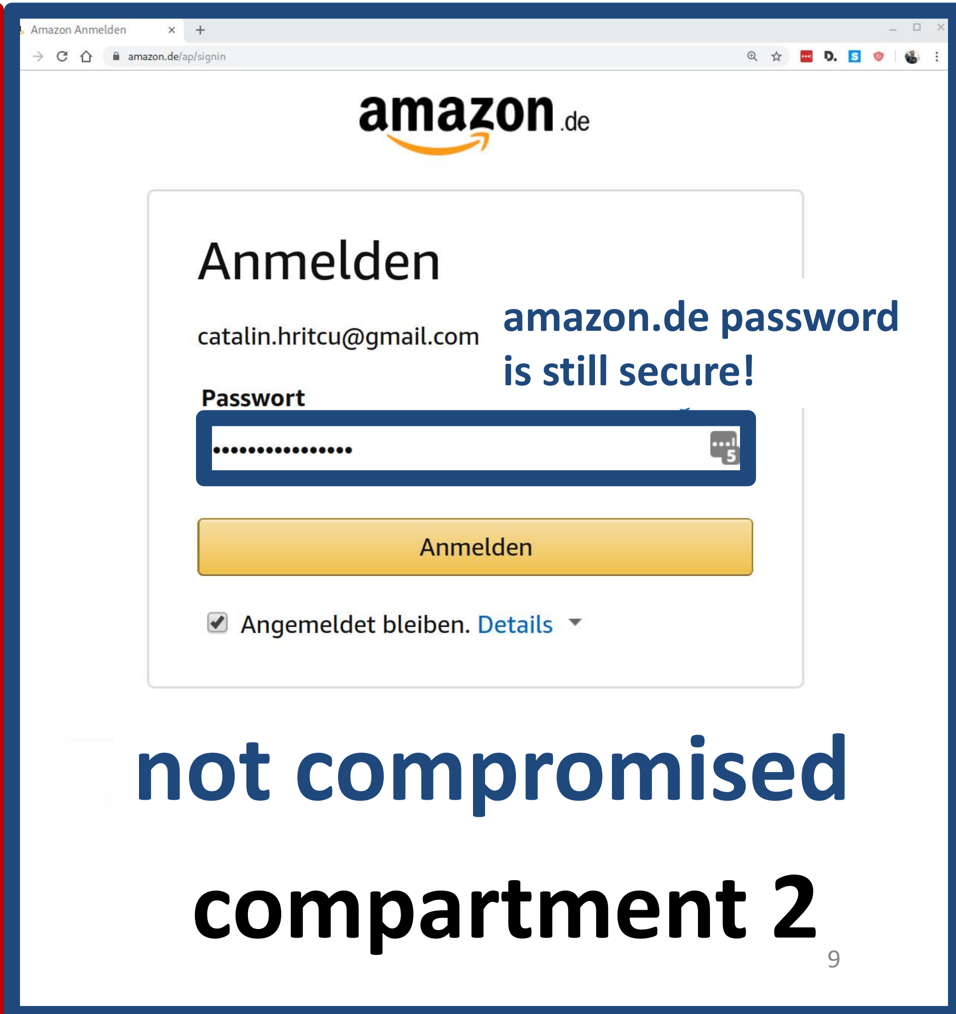

**I've just given my password to the compromised browser controlled by ad.doubleclick.net**

# Compartmentalization can help




compromised

compartment 1




amazon.de password is still secure!

not compromised

compartment 2

## Good news: browsers now compartmentalized!

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

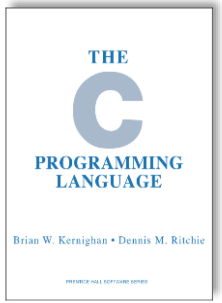
## Bad news, so far:

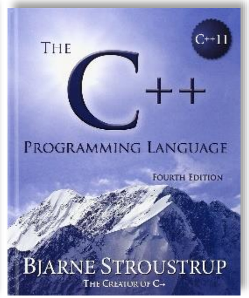
- **limited compartmentalization mechanism**
  - **compartments coarse-grained**
    - can compartmentalize tabs, but not secrets within a tab
  - **compartments can't naturally interact**
    - even for tabs this required big restructuring of web browsers

# 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
  }
}
```

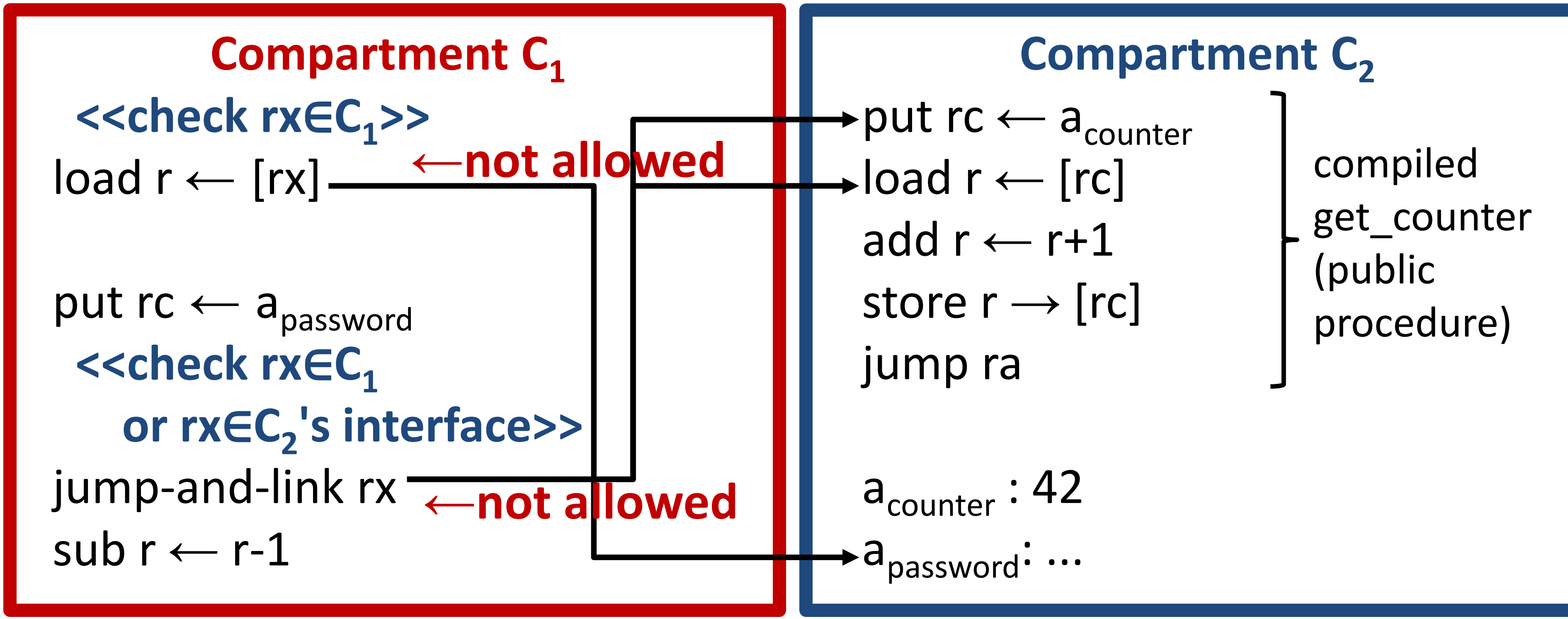
```
compartment C2 {
  private var counter;
  private var password;

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

# Abstractions lost during compilation

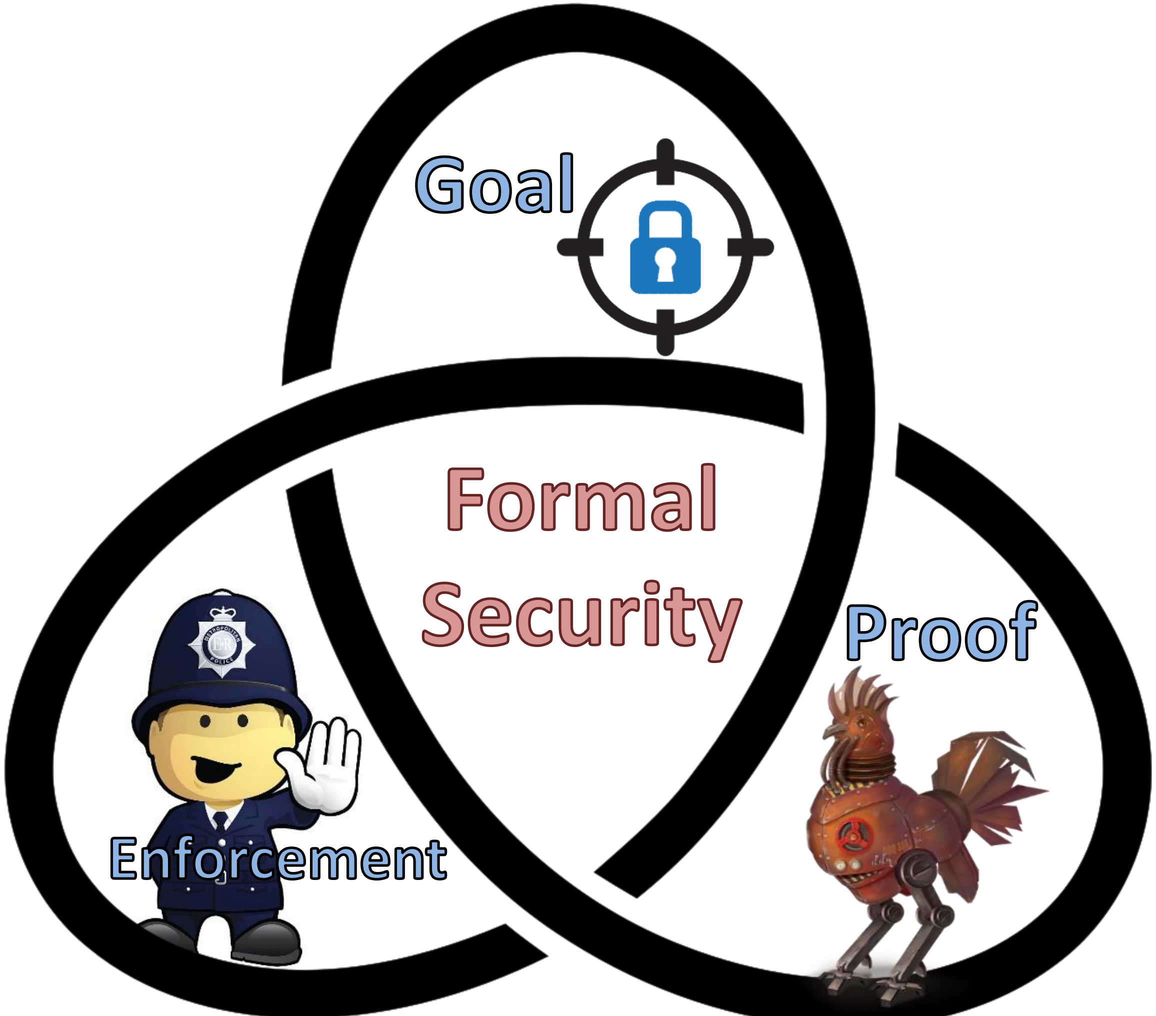
- **Computers don't run C/C++, Java, or F***
  - **Compiler** translates Firefox **from C/C++ to machine code instructions**
- **All compartmentalization abstractions lost during compilation**
  - no procedures, no interfaces, no classes, no objects, no modules, ...
- **Secure compilation**
  - **preserve 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




**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:**

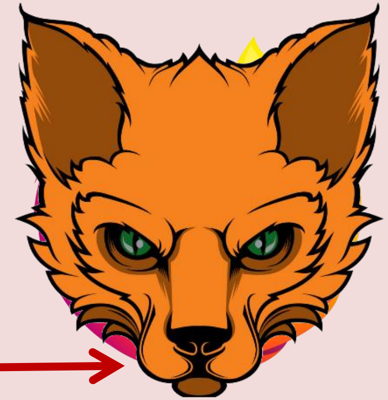
**40.000+ lines of highly-efficient code, mathematically proved to be free of vulnerabilities**

(and functionally correct and side-channel resistant)

# Putting things into perspective

**EverCrypt**
**(verified in F*)**

**40.000 lines**



**Firefox**

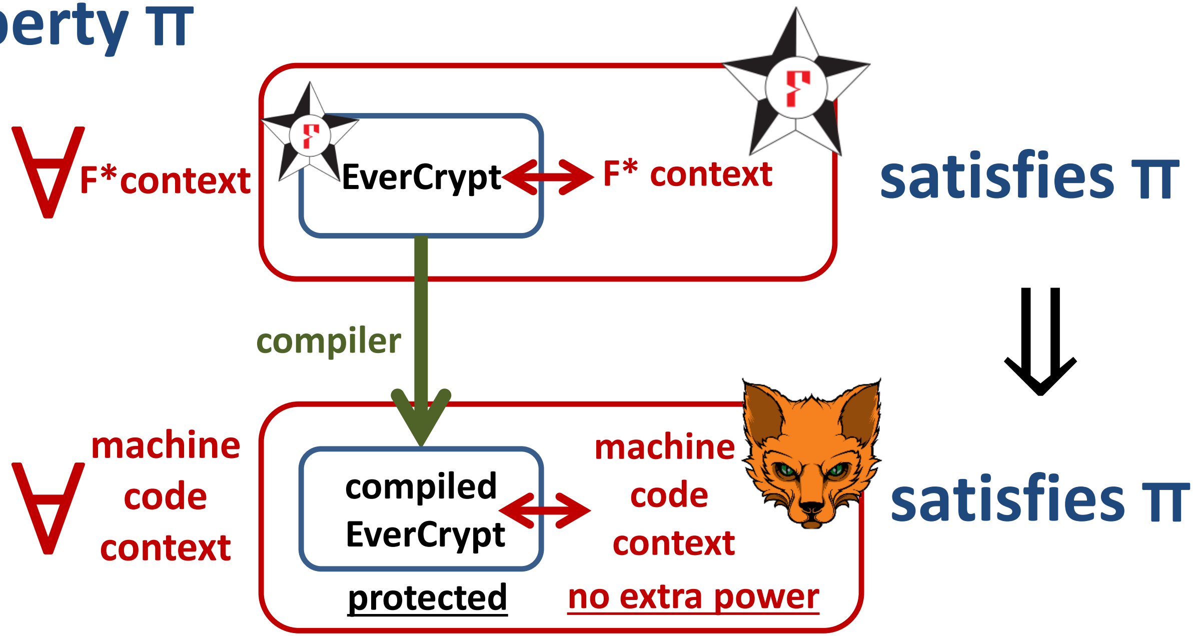
**20.000.000 lines**
**+ external libraries**
**all unverified**

**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"

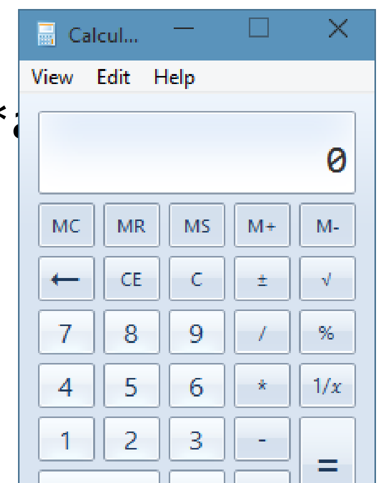
# Extra challenges for our real security definition [CSF'16, CCS'18]

- 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?**

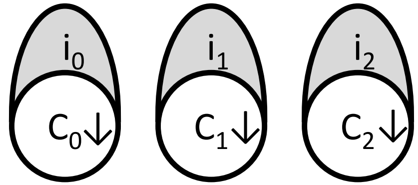
```
#include <string.h>
int main (int argc, char **
    char c[12];
    strcpy(c, argv[1]);
    return 0;
}
```



# 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

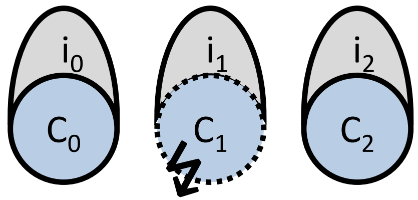
**Security definition:** If




$\rightsquigarrow m$ then

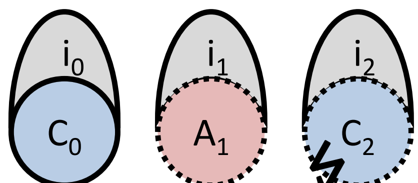
∃ a sequence of component compromises explaining the finite trace $m$ in the source language, for instance $m = m_1 \cdot m_2 \cdot m_3$ and

(1)



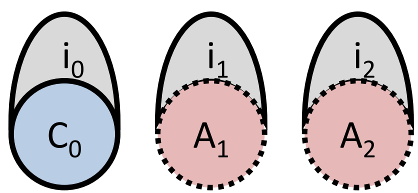

$\rightsquigarrow^* m_1 \cdot \text{Undef}(C_1)$

(2) $\exists A_1.$




$\rightsquigarrow^* m_1 \cdot m_2 \cdot \text{Undef}(C_2)$

(3) $\exists A_2.$




$\rightsquigarrow m_1 \cdot m_2 \cdot m_3$

**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**

**Compartmentalized intermediate language**

new

**Programmable tagged architecture**

**Bare-bone machine**

Buffers, procedures, **compartments**

Intermediate language with **built-in compartmentalization**

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

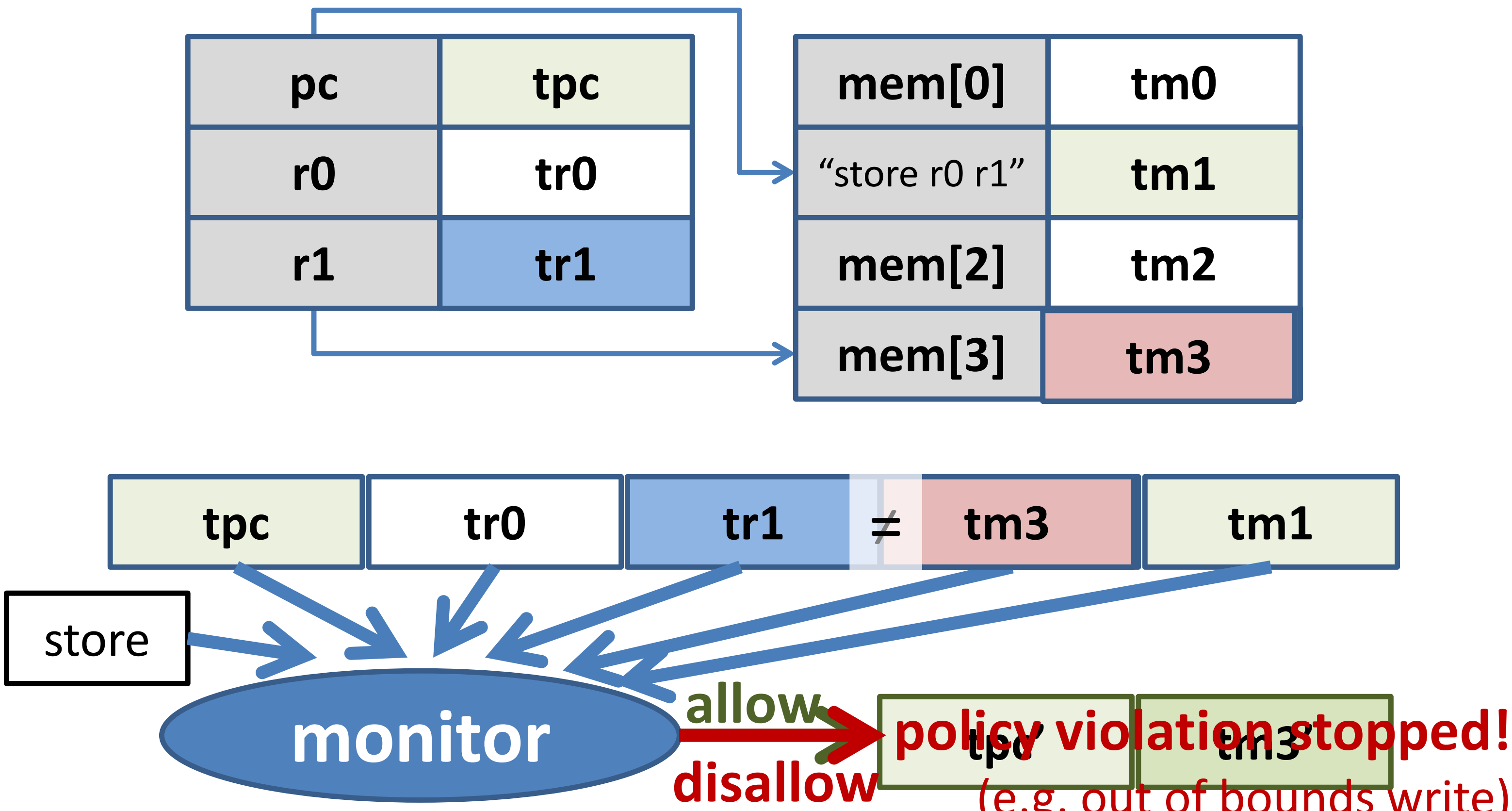
$a_{password}$: ...

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

**Challenges: checks complicated (uncircumventable, efficient)**

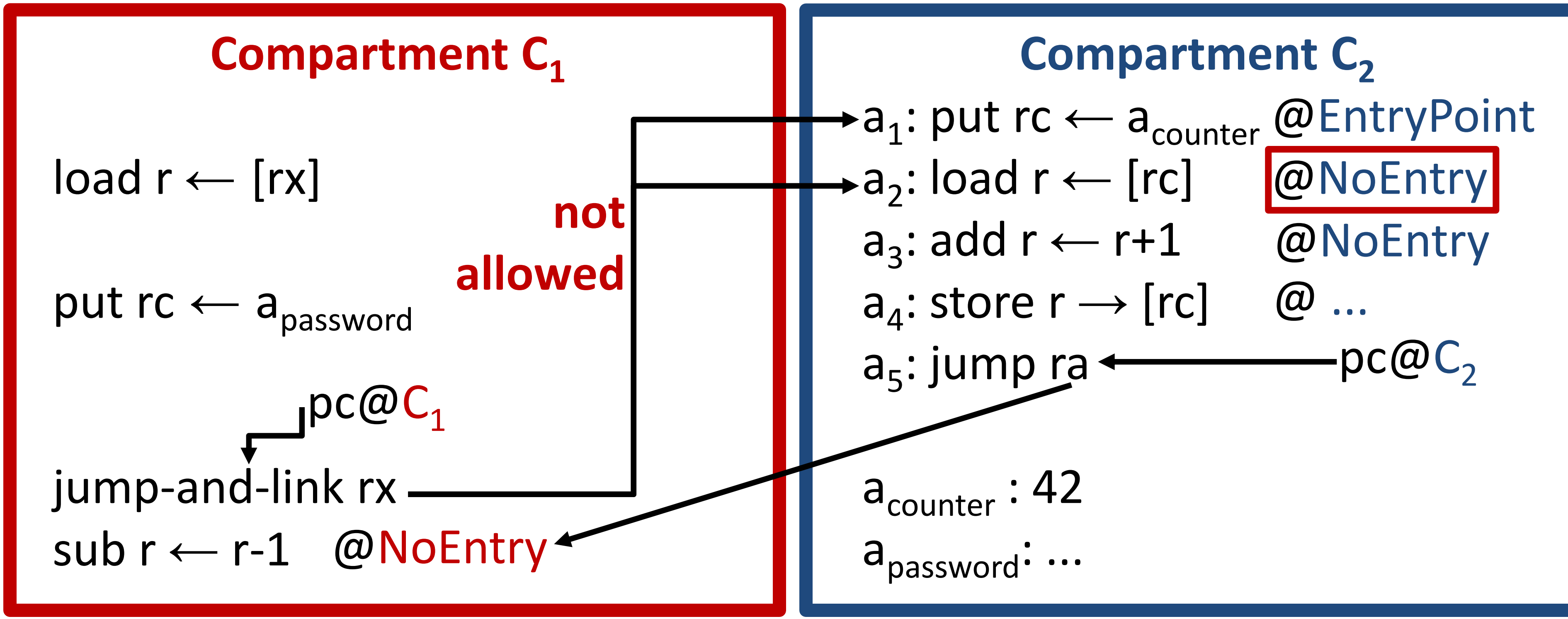
# Micro-Policies [POPL'14, Oakland'15, ASPLOS'15, POST'18, CCS'18]

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




**software monitor’s decision is hardware cached**

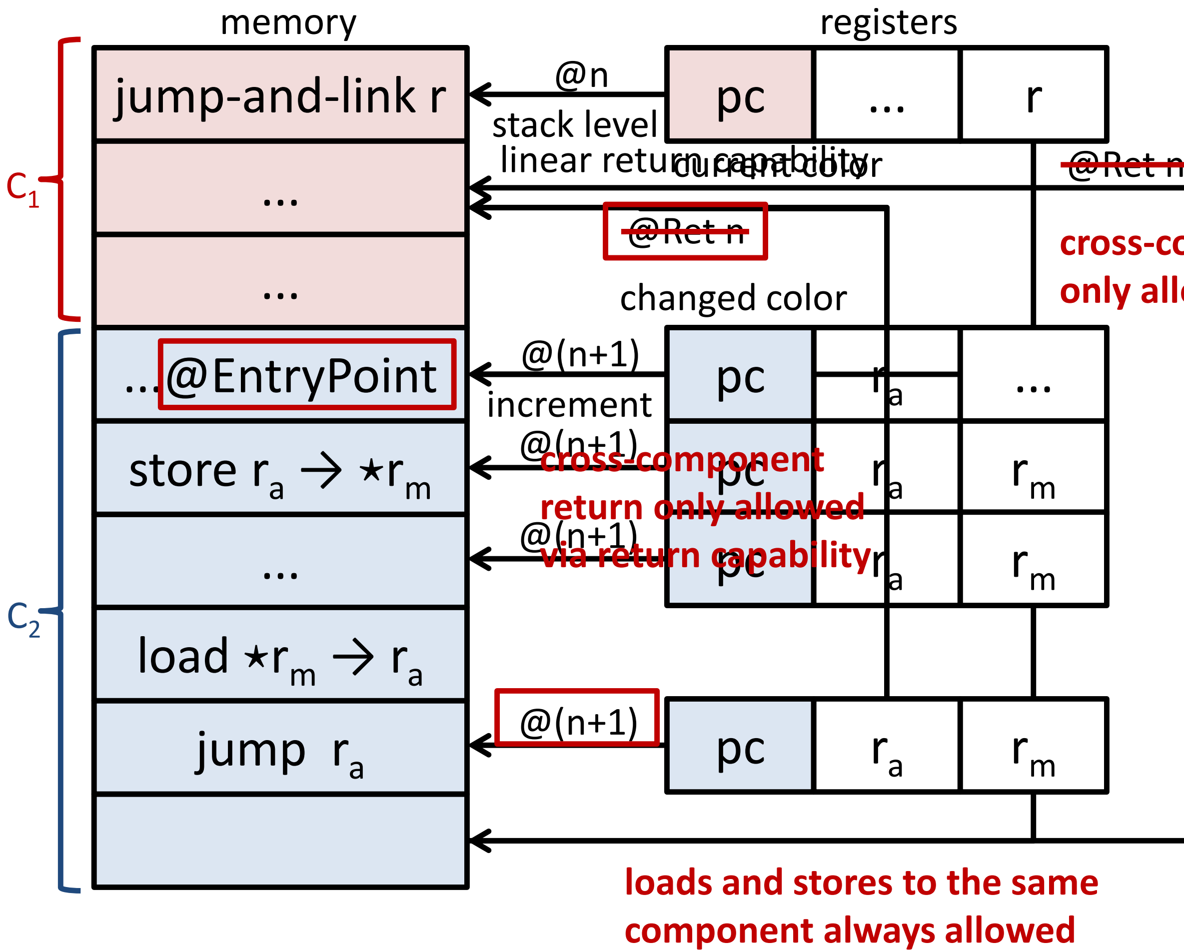
# Compartmentalization micro-policy




**Challenge: making sure returns go to the right place**

# Compartmentalization micro-policy

## (calls and returns)




**invariant:**
at most one
return capability
per call stack level

**Enforcement quickly gets complicated**

# 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**

**Verified**

**Compartmentalized unsafe source**

Buffers, procedures, components interacting via **strictly enforced interfaces**

**generic proof technique**

**20K lines of Coq, mostly proofs**

**Compartmentalized abstract machine**

Simple RISC abstract machine with **build-in compartmentalization**

**software fault isolation**

**Micro-policy machine**

**Bare-bone machine**

**Tag-based reference monitor enforcing:**
- component separation
- procedure call and return discipline

(linear capabilities / linear entry points)

**Inline reference monitor enforcing:**
- component separation
- procedure call and return discipline

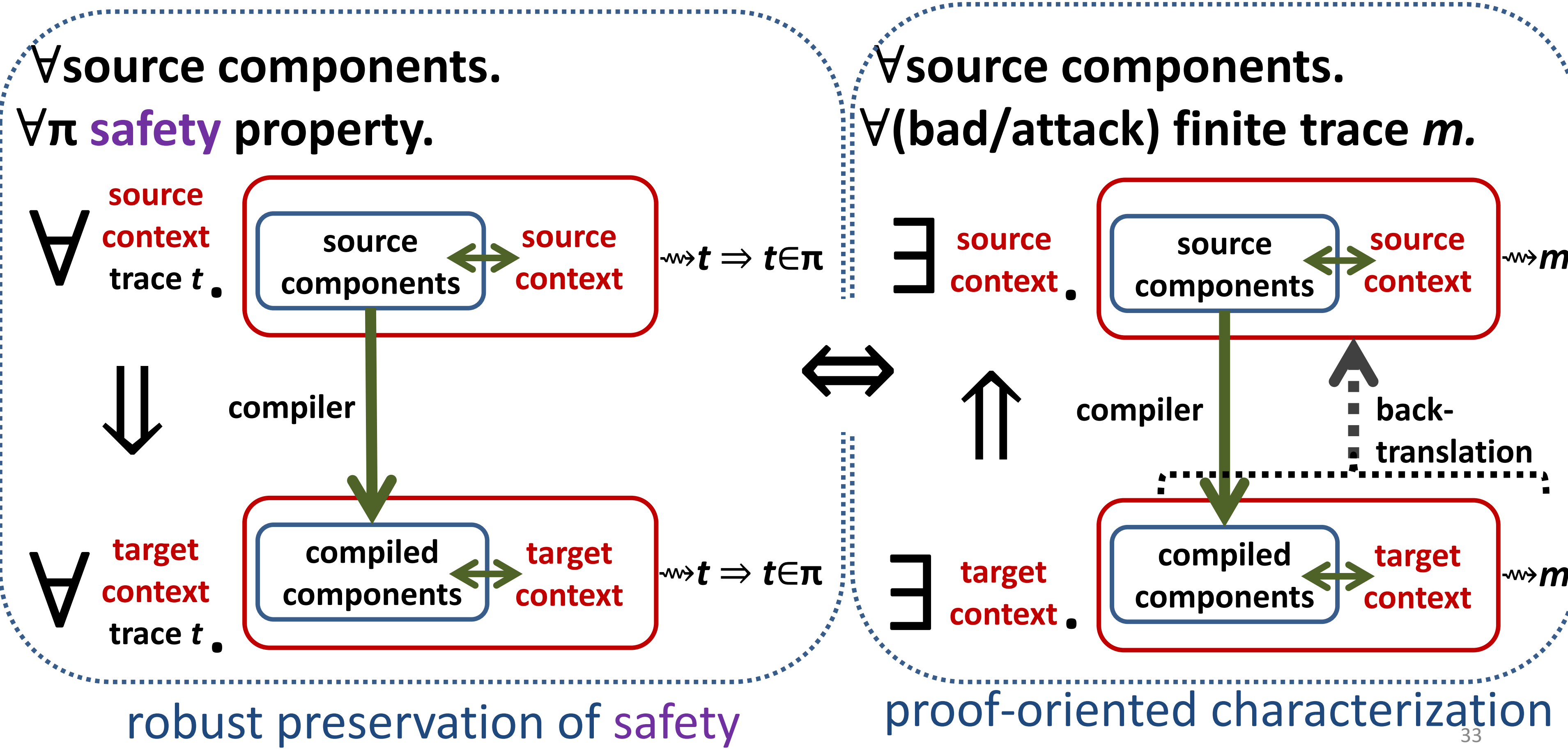
(program rewriting, shadow call stack)

**Systematically tested (with QuickChick)**

https://secure-compilation.github.io

We reduce our proof goal to a variant of:

# Robust Safety Preservation



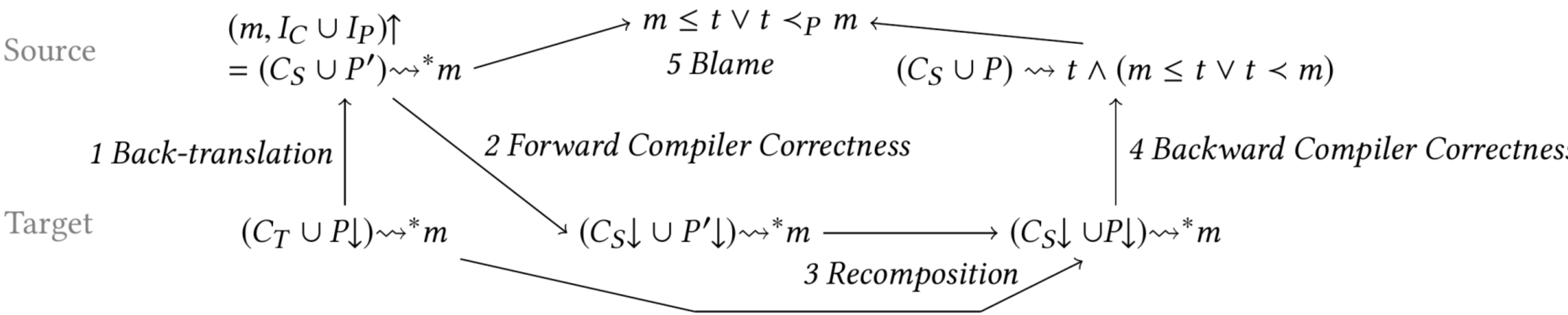
# Scalable proof technique

**(for our variant of Robust Safety Preservation)**

*1*. back-translating **finite trace prefix** to **whole source program**

*2+4*. compiler correctness proof (à la CompCert) **used as a black-box**

*3+5*. also simulation proofs, but at a single level



# 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

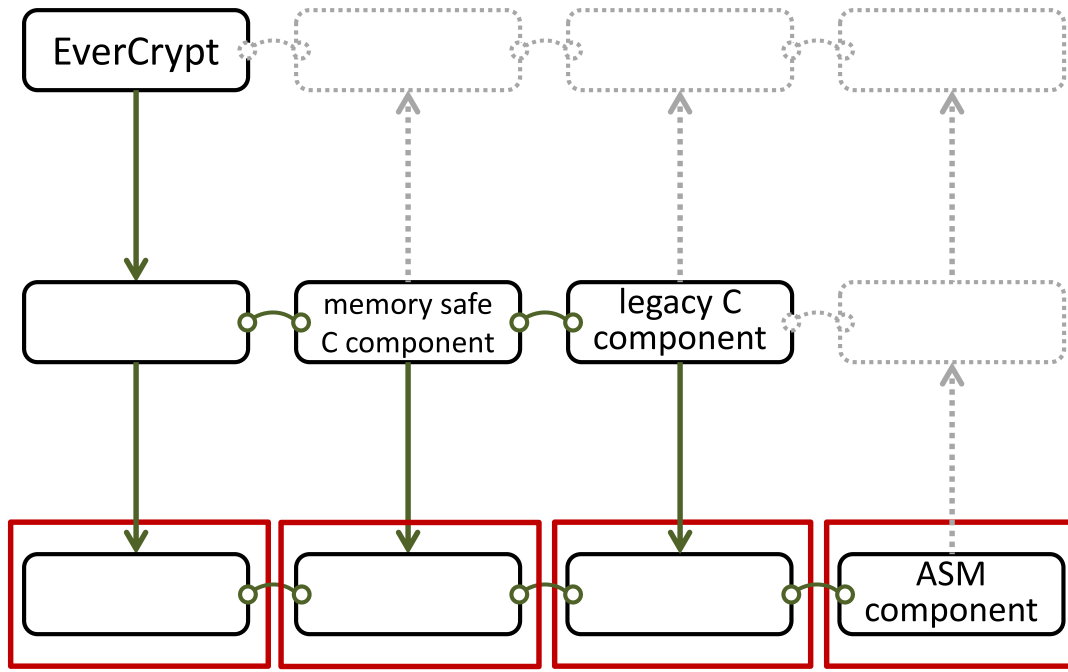
**language**

**C language**

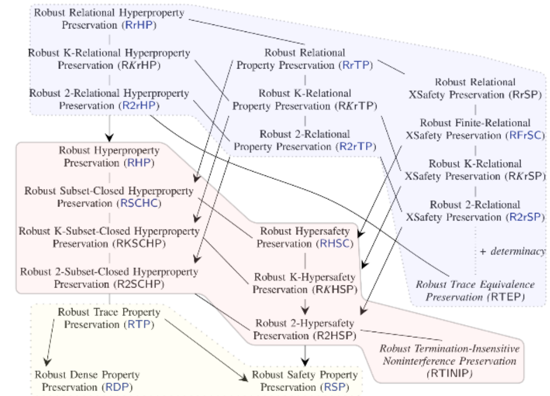
+ components
+ memory safety

**ASM language**

(RISC-V + micro-policies)



# Going beyond Robust Preservation of Safety




## Journey Beyond Full Abstraction (CSF 2019)



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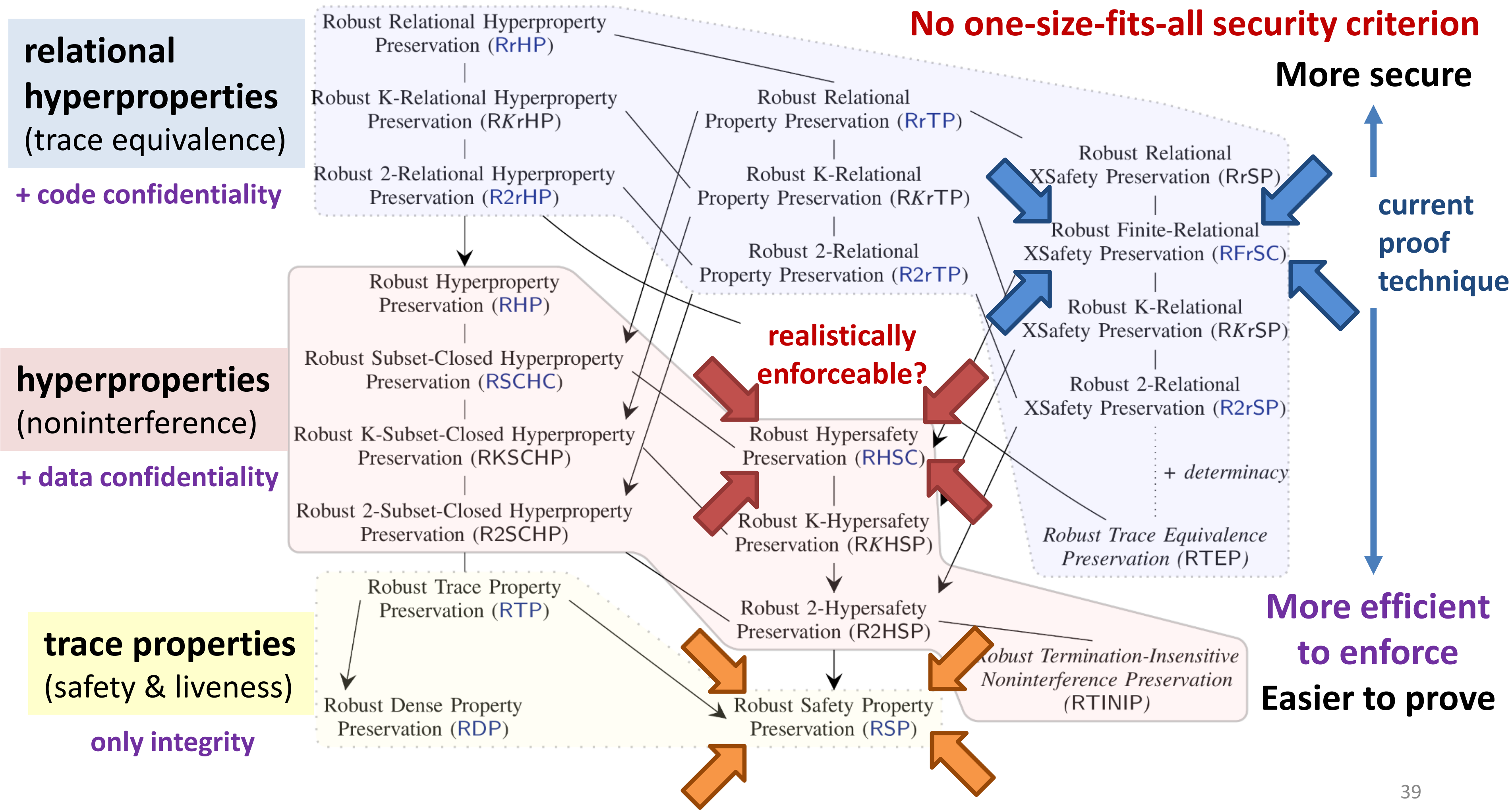
Stanford & CISPA

# Going beyond Robust Preservation of Safety [CSF'19]



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