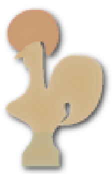
When Good Components Go Bad

Formally Secure Compilation Despite Dynamic Compromise



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https://secure-compilation.github.io

10 Co-authors ⇒ 100% acceptance rate

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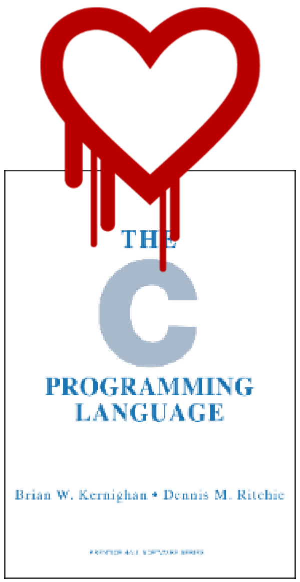
Compartmentalization can defend against devastating low-level attacks

Inherently insecure languages like C

- any **buffer overflow** can be catastrophic
- ~100 different **undefined behaviors** in the usual C compiler:
  - **use after frees and double frees, invalid casts, signed integer overflows, ...**
- **root cause**, but very challenging to fix:
  - **efficiency**, precision, scalability, backwards compatibility, deployment



Compartmentalization mitigation

- **Break up security-critical applications** into **mutually distrustful components** with **clearly specified privileges**
- **Protect component abstraction all the way down**
  - separation, static privileges, call-return discipline, types, ...
- **Compartmentalizing compilation chain:**
  - compiler, linker, loader, runtime, system, hardware
- **Base this on efficient enforcement mechanisms:**
  - OS processes (all web browsers)
  - software fault isolation (SFI)
  - hardware enclaves (SGX)
  - WebAssembly (web browsers)
  - capability machines
  - tagged architectures

Strong security!?

- **Security guarantees one can make fully water-tight**
  - beyond just "increasing attacker effort"
- **Intuitively, ...**

... **a vulnerability in one component does not immediately destroy the security of the whole application**

... **since each component is protected from all the others**

... and each component receives protection as long as it has not been compromised (e.g. by a buffer overflow)

Can we formalize this intuition?

What is a compartmentalizing compilation chain supposed to enforce precisely?

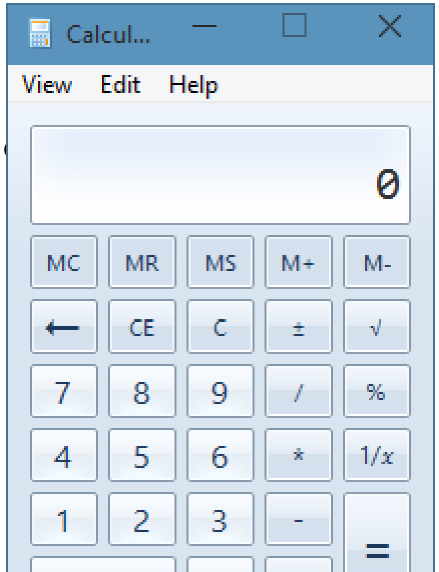
This paper answers this question:

Formal definition expressing the end-to-end security guarantees of compartmentalization

Challenge formalizing security of mitigations

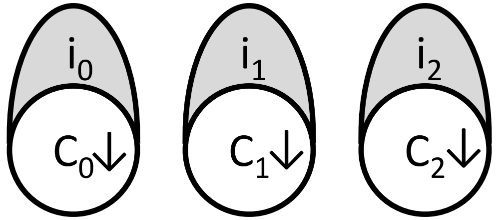
- **We want source-level security reasoning principles**
  - easier to **reason about security in the source language** if and application is compartmentalized
- **... even in the presence of undefined behavior**
  - can't be expressed at all by source language semantics!
  - **what does the following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

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



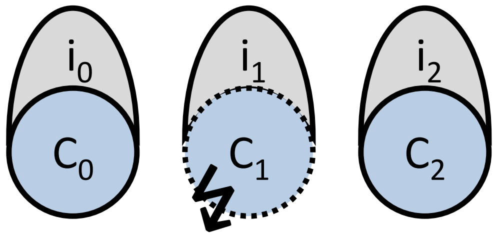
Compartmentalizing compilation should ...

- **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

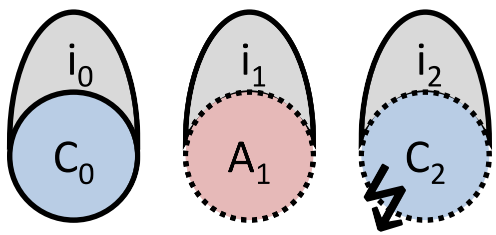
Security definition: If 

$\rightsquigarrow t$ then

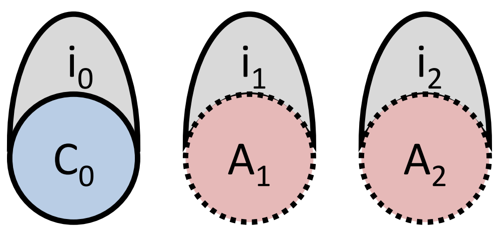
$\exists$ a sequence of component compromises explaining the finite trace t in the source language, for instance $t = m_1 \cdot m_2 \cdot m_3$ and

(1) 

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

(2) $\exists A_1.$ 

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

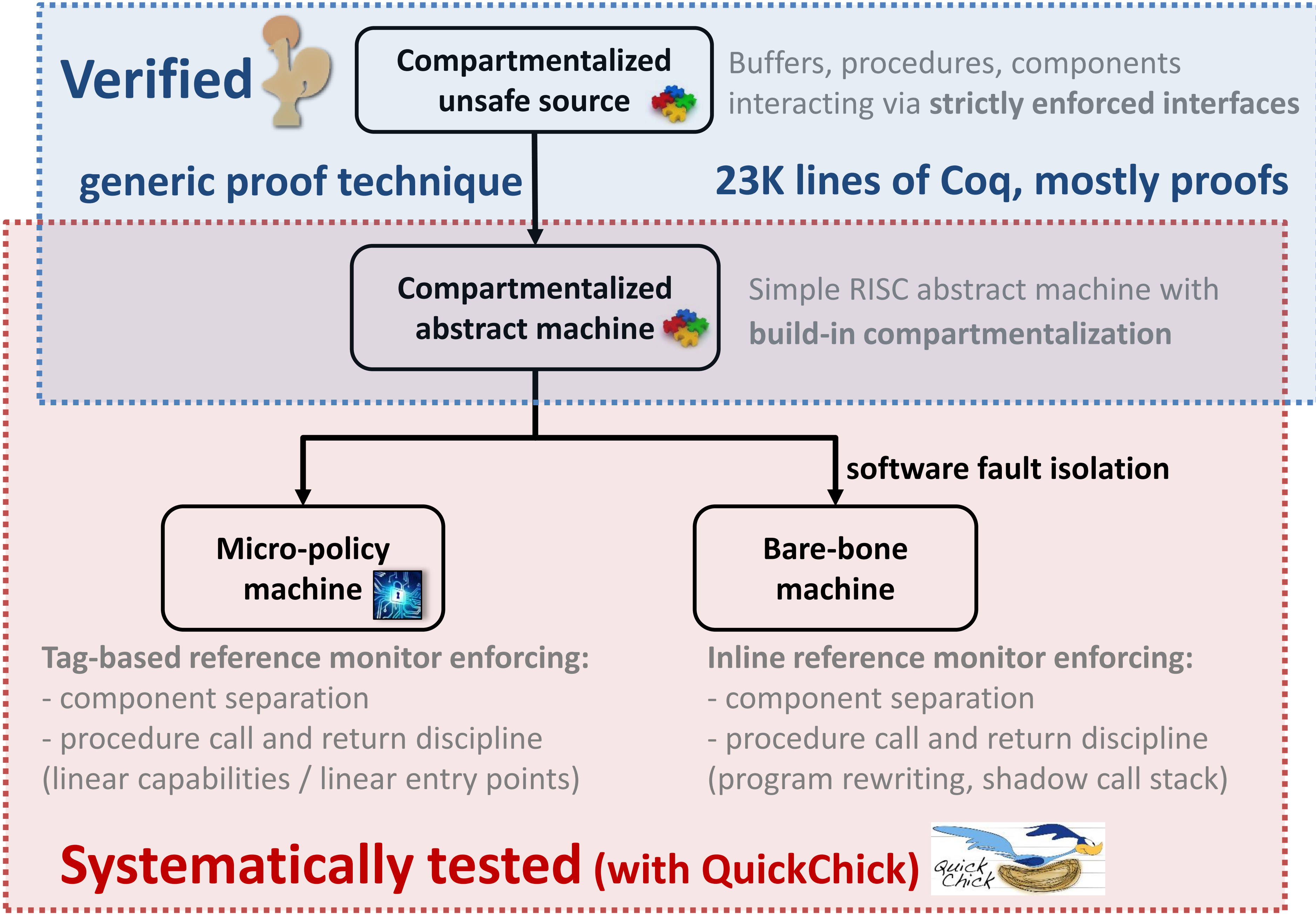
(3) $\exists A_2.$ 

$\rightsquigarrow m_1 \cdot m_2 \cdot m_3$

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

Proof-of-concept formally secure compilation chain in Coq

Illustrates our formal definition



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When Good Components Go Bad

- **Formalized security of compartmentalization**
  - **first definition** supporting **dynamic compromise**
  - **restricting undefined behavior spatially** and **temporally**

- **Proof-of-concept secure compilation chain in Coq**
  - **software fault isolation** or **tag-based reference monitor**
- **Generic definition and proof technique**
  - **we expect them to extend and scale well (ask me about it!)**

- **We're hiring!**
  - **PostDocs, Young Researchers**, Students

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Making this more practical ... next steps:

- **Scale formally secure compilation chain to C language**
  - ongoing: allow **shared memory** and **pointer passing** (capabilities)
  - eventually support enough of C to **measure and lower overhead**
  - eventually support **more enforcement mechanisms** (back ends)
- **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 (eg confidentiality)**

  [Exploring robust property preservation for secure compilation, arXiv:1807.04603]

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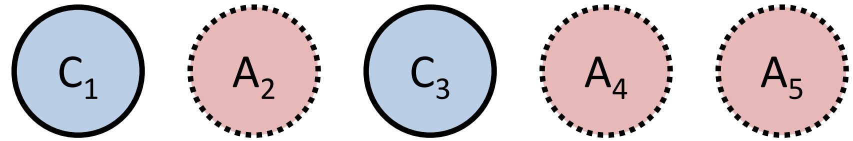
BACKUP SLIDES

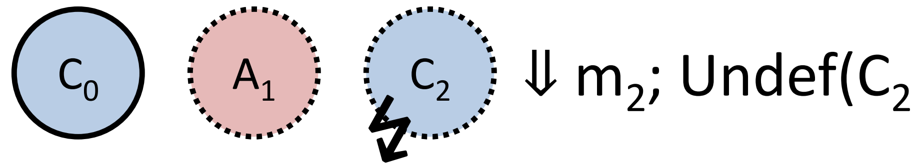
Now we know what these words mean!

(at least in the setting of compartmentalization for unsafe low-level languages)

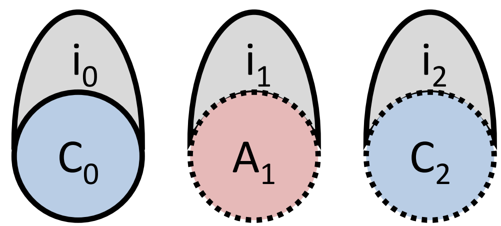
Mutual distrust

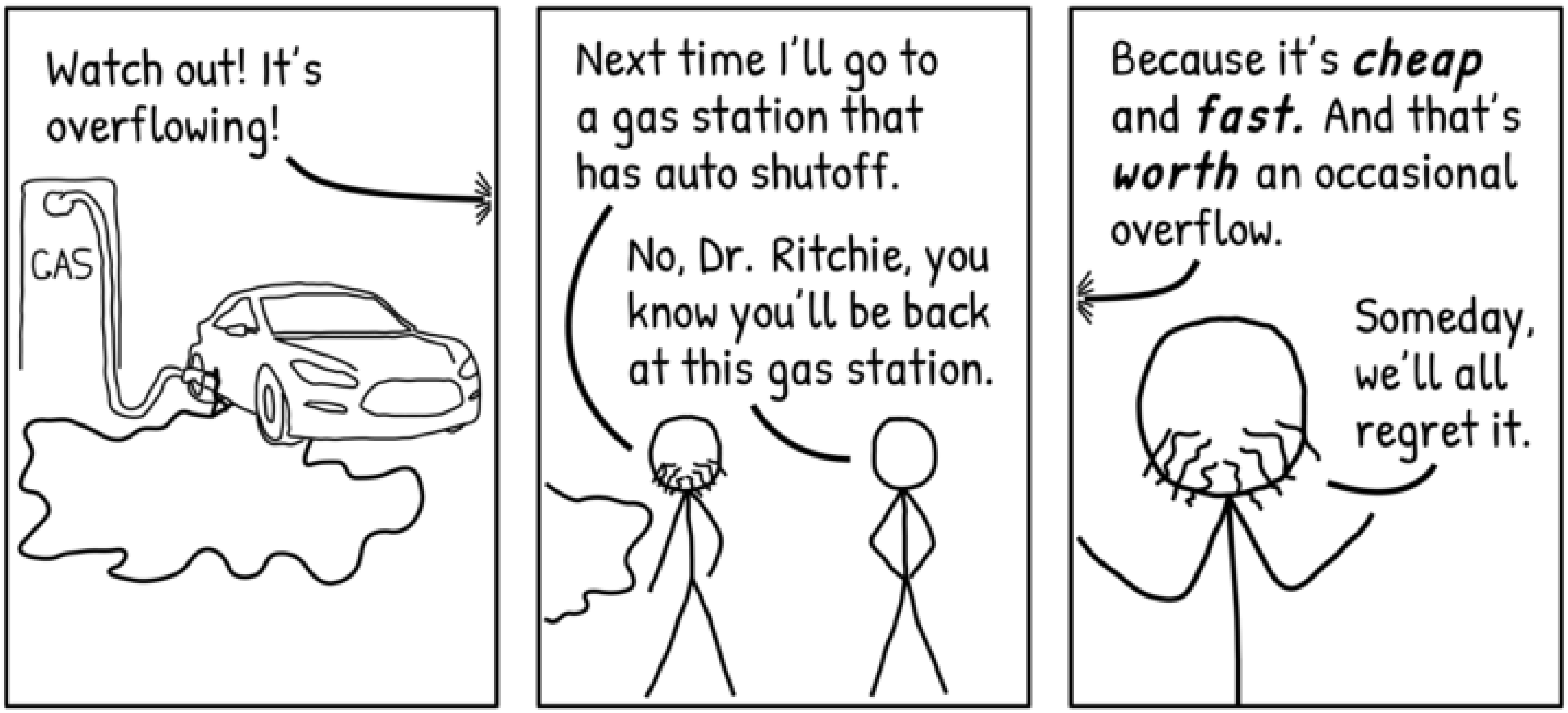


Dynamic compromise



Static privilege





Buffer Overflow.

icanbarelydraw.com

Restricting undefined behavior

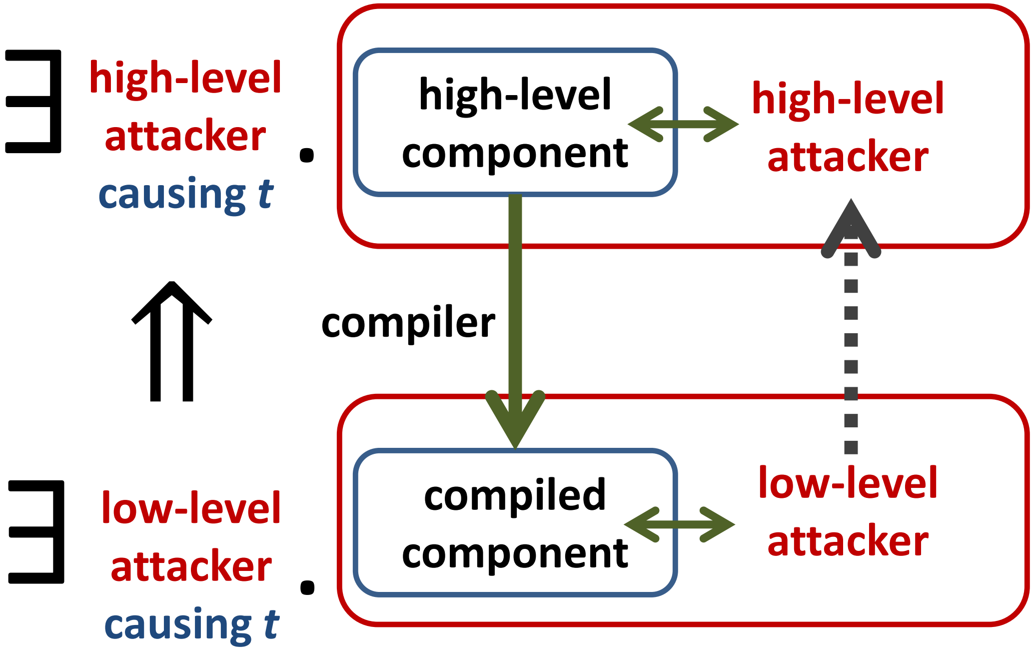
- **Mutually-distrustful components**
  - restrict **spatial** scope of undefined behavior
- **Dynamic compromise**
  - restrict **temporal** scope of undefined behavior
  - undefined behavior = **observable trace event**
  - **effects of undefined behavior**
    shouldn't percolate before earlier observable events
    - careful with code motion, backwards static analysis, ...
  - CompCert **already offers** this saner temporal model
  - GCC and LLVM **currently violate** this model

Dynamic compromise

- each component gets guarantees as long as it has not encountered undefined behavior
- a component only loses guarantees after an attacker discovers and exploits a vulnerability
- the mere existence of vulnerabilities doesn't immediately make a component compromised

We build this on Robust Compilation

∀(bad attack) trace *t*



robust trace property preservation
(robust = in adversarial context)

intuition:

- **stronger** than compiler correctness (i.e. trace property preservation)
- **confidentiality not preserved** (i.e. no hyperproperties)
- **less extensional** than fully abstract compilation

Advantages: **easier to realistically achieve and prove at scale**

useful: preservation of **invariants** and other **integrity properties**

generalizes to preserving [relational] hyperproperties!

extends to unsafe languages, supporting dynamic compromise

Scalable proof technique

for our extension of robustly safe compilation

1. **back-translating finite trace prefixes to whole source programs**
   – limitation: only works for preserving (hyper)safety
2. **generically defined semantics for partial programs**
   – related to whole-program semantics via **trace composition** and **decomposition lemmas**
3. **using whole-program compiler correctness proof (à la CompCert) as a black-box**
   – for moving back and forth between source and target

all this yields much simpler and more scalable proofs

Making this stronger ... beyond safety

[Exploring Robust Property Preservation For Secure Compilation, arXiv...]