$$\underbrace{\text{Formally Secure Compilation}}^{\text{Compartmentalizing}}$$

Compartmentalizing Formally Secure Compilation

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https://secure-compilation.github.io

Course outline

- **0. Compiler correctness**
  - as Trace Property Preservation
- **1. Secure interoperability with lower-level code**
  - Secure 2-Compartmentalizing Compilation as **Robust** Property Preservation
  - Property ∈ **Trace Properties**, Hyperproperties, Relational ...
- **2. Secure compilation despite dynamic compromise**
  - Compartmentalizing Compilation for **Unsafe Languages**
  - Restricting the temporal + spatial scope of **undefined behavior**

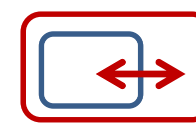
Devastating low-level attacks

Part 2: give meaning to mitigation (protected components)

inherently insecure languages like C/C++

- **e.g. memory unsafe**: any buffer overflow is catastrophic allowing remote attackers to gain complete control
- ~100 different **undefined behaviors** in usual C compiler

insecure interoperability with lower-level code



- even code in **more secure languages (Java, OCaml, Rust)** has to interoperate with **low-level code (C, C++, ASM)**
- **insecure interoperability**: all source-level guarantees lost

Part 1: formalize what it means to solve this problem

Part 2 of 2

When Good Components Go Bad

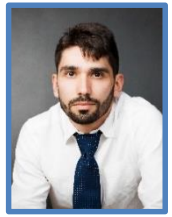
Secure Compilation Despite Dynamic Compromise

To appear @ Computer and Communications Security (CCS 2018)

https://arxiv.org/abs/1802.00588

Collaborators for Part 2

Carmine Abate



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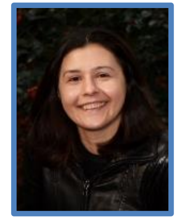

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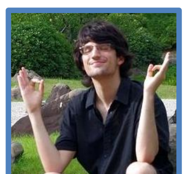

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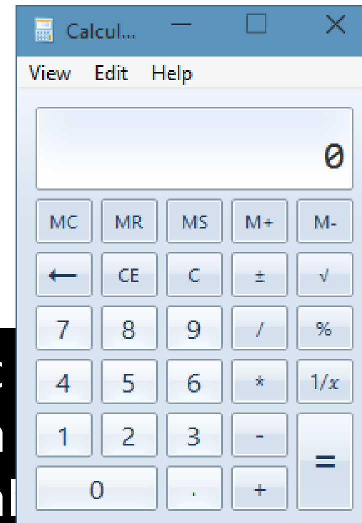
Undefined behavior

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



erflow

```
$ gcc target.c
$ ./a.out haha
$ ./a.out hahal                haha
zsh: segmentation fault (core dumped)
$ ./exploit.sh | a.out
```

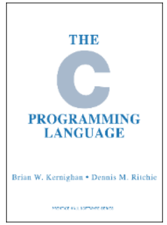
Practical mitigation: compartmentalization

- **Main idea:**
  - break up security-critical C applications into **mutually distrustful components** with clearly specified privileges & interacting via strictly enforced interfaces
- **Strong security guarantees & interesting attacker model**
  - "a vulnerability in one component does not immediately destroy the security of the whole application"
  - "each component is protected from all the others"
  - "each components receives guarantees as long as it has not encountered undefined behavior"

Goal 1: Formalize this

Goal 2: Build secure compilation chains

- **Add components to C**
  - interacting only via **strictly enforced interfaces**
- **Enforce "component C" abstractions:**
  - component separation, call-return discipline, ...
- **Secure compilation chain:**
  - compiler, linker, loader, runtime, system, hardware
- **Use efficient enforcement mechanisms:**
  - OS processes (all web browsers)
  - software fault isolation (SFI)
  - hardware enclaves (SGX)
  - WebAssembly (web browsers)
  - capability machines
  - tagged architectures



Goal 1: Formalizing the security of compartmentalizing compilation

Restricting undefined behavior

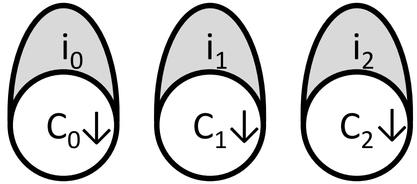
- **Mutually-distrustful components**
  - restrict **spatial** scope of undefined behavior
- **Dynamic compromise**
  - restrict **temporal** scope of undefined behavior
  - undefined behavior = **observable trace event**
  - **effects of undefined behavior**
    shouldn't percolate before earlier observable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

Dynamic compromise

- each component gets guarantees as long as it has not encountered undefined behavior

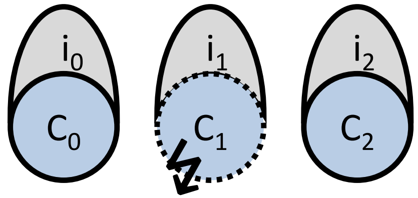
- a component only loses guarantees after an attacker discovers and exploits a vulnerability

- the mere existence of vulnerabilities doesn't immediately make a component compromised

If 

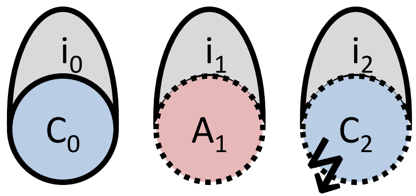
$\rightsquigarrow t$ then

∃ a **dynamic compromise scenario** explaining *t* in source language for instance leading to the following compromise sequence:

(0) 

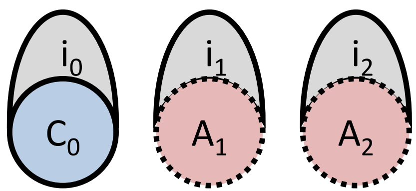
$\rightsquigarrow^* m_1 \cdot \mathrm{Undef}(C_1)$

$\leq$

(1) $\exists A_1.$ 

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

$\leq$

(2) $\exists A_2.$ 

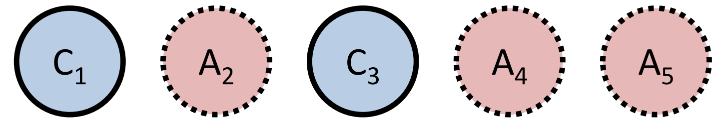
$\rightsquigarrow t$

Trace is very helpful
- detect undefined behavior
- rewind execution

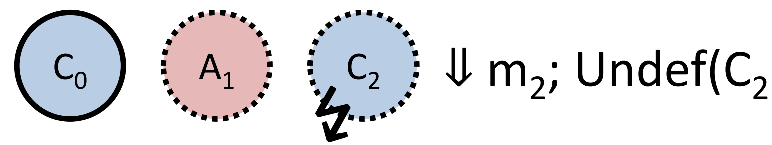
Now we know what these words mean!

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

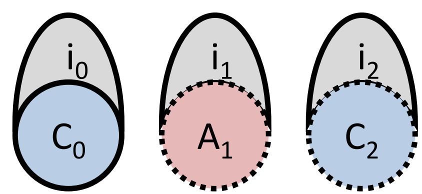
Mutual distrust



Dynamic compromise



Static privilege



Goal 2: Towards building secure compilation chains

(mostly)
Verified
in Coq

Compartmentalized unsafe source

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

Compartmentalized abstract machine

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

software fault isolation

Micro-policy machine

Tag-based reference monitor enforcing:
- component separation
- procedure call and return discipline
(linear capabilities / linear entry points)

Bare-bone machine

Inline reference monitor enforcing:
- component separation
- procedure call and return discipline
(program rewriting, shadow call stack)

Systematically tested (with QuickChick)

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

- **Scale up to more of C**
  - first step: allow pointer passing (capabilities)
- **Verify compartmentalized applications**
  - put the source-level reasoning principles to work
- **Extend all this to dynamic component creation**
- **... and dynamic privileges:**
  - capabilities, dynamic interfaces, HBAC, ...
- **Support other enforcement mechanisms (back ends)**
- **Measure & lower overhead**

Wrapping up

- **1. Secure interoperability with lower-level code**
  - **exploring a continuum, security vs efficiency tradeoff**
- **2. Secure compilation despite dynamic compromise**
  - **restricting the scope of undefined behavior**
    - **spatially** to the component that caused it
    - **temporally** by treating UB as an observable trace event
- **We're hiring! now!**
  - **PostDocs, Young Researchers,** Interns, PhD students