SECOMP
Efficient Formally Secure Compilers to a Tagged Architecture

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Prosecco team

5 year vision

European Research Council new grant
Computers are insecure

• devastating low-level vulnerabilities
• programming languages, compilers, and hardware architectures
  – designed in an era of scarce hardware resources
  – too often trade off security for efficiency
• the world has changed (2016 vs 1972*)
  – security matters, hardware resources abundant
  – time to revisit some tradeoffs

* “...the number of UNIX installations has grown to 10, with more expected...”
  -- Dennis Ritchie and Ken Thompson, June 1972
Hardware architectures

• Today’s processors are mindless bureaucrats
  – “write past the end of this buffer” ... yes boss!
  – “jump to this untrusted integer” ... right boss!
  – “return into the middle of this instruction” ... sure boss!

• Software bears most of the burden for security

• Manufacturers have started looking for solutions
  – 2015: Intel Memory Protection Extensions (MPX) and Intel Software Guard Extensions (SGX)
  – 2016: Oracle Silicon Secured Memory (SSM)
Unsafe low-level languages

- C (1972) and C++ **undefined behavior**
  - including buffer overflows, checks too expensive
  - compilers optimize aggressively assuming undefined behavior will simply not happen

- **Programmers bear the burden for security**
  - just write secure code ... all of it

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**[PATCH] CVE-2015-7547 --- glibc getaddrinfo() stack-based buffer overflow**

- **DNS queries**

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The glibc project thanks the Google Security Team and Red Hat for reporting the security impact of this issue, and Robert Holiday of Ciena for reporting the related bug 18665.
Safer high-level languages

• **memory safe** (at a cost)

• **useful abstractions** for writing secure code:
  – GC, type abstraction, modules, immutability, ...

• **not immune to low-level attacks**
  – large runtime systems, in C++ for efficiency
  – **unsafe interoperability with low-level code**
    • libraries often have large parts written in C/C++
    • enforcing abstractions all the way down too expensive
Summary of the problem

• 1. inherently insecure low-level languages
  – memory unsafe: any buffer overflow can be catastrophic allowing remote attackers to gain complete control

• 2. unsafe interoperability with lower-level code
  – even code written in safer high-level languages has to interoperate with insecure low-level libraries
  – unsafe interoperability: all high-level safety guarantees lost

• Today’s languages & compilers plagued by low-level attacks
  – hardware provides no appropriate security mechanisms
  – fixing this purely in software would be way too inefficient
Key enabler: Micro-Policies

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

software monitor’s decision is hardware cached
Key enabler: Micro-Policies

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

```
<table>
<thead>
<tr>
<th>pc</th>
<th>tpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>r0</td>
<td>tr0</td>
</tr>
<tr>
<td>r1</td>
<td>tr1</td>
</tr>
</tbody>
</table>
```

```
<table>
<thead>
<tr>
<th>mem[0]</th>
<th>tm0</th>
</tr>
</thead>
<tbody>
<tr>
<td>“store r0 r1”</td>
<td>tm1</td>
</tr>
<tr>
<td>mem[2]</td>
<td>tm2</td>
</tr>
<tr>
<td>mem[3]</td>
<td>tm3</td>
</tr>
</tbody>
</table>
```

**monitor**

```
<table>
<thead>
<tr>
<th>tpc</th>
<th>tr0</th>
<th>tr1 ≠ tm3</th>
<th>tm3</th>
<th>tm1</th>
</tr>
</thead>
</table>
```

*store*

policy violation stopped! (e.g. out of bounds write)
Micro-policies are cool!

- **low level + fine grained**: unbounded per-word metadata, checked & propagated on each instruction
- **flexible**: tags and monitor defined by software
- **efficient**: software decisions hardware cached
- **expressive**: complex policies for secure compilation
- **secure** and **simple** enough to verify security in Coq
- **real**: FPGA implementation on top of RISC-V
Expressiveness

- information flow control (IFC) [POPL’14]
- monitor self-protection
- protected compartments
- dynamic sealing
- heap memory safety
- code-data separation
- control-flow integrity (CFI)
- taint tracking
- ...

Verified (in Coq) [Oakland’15]

Evaluated (<10% runtime overhead) [ASPLOS’15]
SECOMP grand challenge

Use micro-policies to build the first efficient formally secure compilers for realistic programming languages

1. Provide secure semantics for low-level languages
   - C with protected components and memory safety

2. Enforce secure interoperability with lower-level code
   - ASM, C, and F* \([F^* = \text{ML + verification}]\)
Formally verify: **full abstraction**

holy grail of secure compilation, enforcing abstractions all the way down

- program behavior
- compiler correctness (e.g. CompCert)
- program behavior

- source component
- high-level attacker

- target component
- protected
- low-level attacker
- no extra power

- compiler
- full abstraction

- e.g. arbitrary machine code
Formally verify: **full abstraction**

holly grail of secure compilation, enforcing abstractions all the way down

Benefit: sound security reasoning in the source language
forget about compiler chain (linker, loader, runtime system)
forget that libraries are written in a lower-level language
Fully abstract compilation, definition

∃ high-level attacker

1\textsuperscript{st} high-level component \rightleftarrows \text{high-level attacker}

compiler

1\textsuperscript{st} compiled component \rightleftarrows \text{low-level attacker}

∃ low-level attacker

∃ high-level attacker

2\textsuperscript{nd} high-level component \rightleftarrows \text{high-level attacker}

compiler

2\textsuperscript{nd} compiled component \rightleftarrows \text{low-level attacker}
SECOMP: achieving full abstraction at scale

F* language
(ML + verification)

C language
+ memory safety
+ components

ASM language
(RISC-V + micro-policies)

protecting higher-level abstractions

miTLS*

SecF* + SecML

memory safe C component

legacy C component

protecting component boundaries

CompSec+

CompSec

ASM component
Protecting component boundaries

• Add mutually distrustful components to C
  – interacting only via strictly enforced interfaces

• CompSec compiler chain (based on CompCert)
  – propagate interface information to produced binary

• Micro-policy simultaneously enforcing
  – component separation
  – type-safe procedure call and return discipline

• Interesting attacker model
  – extending full abs. to mutual distrust + unsafe source

Recent preliminary work, joint with Yannis Juglaret et al
Compartmentalization micro-policy

Compartmentalization micro-policy

Compartmentalization micro-policy

Compartmentalization micro-policy

[Jal r
...
...
...@EntryPoint
Store \( r_a \to *r_m \)
...
Load \( *r_m \to r_a \)
Jump \( r_a \)]

Registers

\( \text{pc} \quad r_a \quad ... \)

Memory

\( C_1 \)

\( C_2 \)

Compartmentalization micro-policy

Compartmentalization micro-policy

Compartmentalization micro-policy

memory

Jal r
...
...
...@EntryPoint
Store \( r_a \to \ast r_m \)
...
Load \( \ast r_m \to r_a \)
Jump \( r_a \)

registers

linear return capability

\( \ast \)

\( \ast \)

\( \ast \)

\( \ast \)

\( \ast \)

\( \ast \)

loads and stores to the same component always allowed
Compartmentalization micro-policy

memory

Jal r
...
...
...@EntryPoint
Store \( r_a \rightarrow *r_m \)
...
Load \( *r_m \rightarrow r_a \)
Jump \( r_a \)

registers

linear return capability

@Ret n

\( \text{@Ret n} \)

\( \text{paren} \)

\( \text{pc} \)

@\( (n+1) \)

\( \text{ra} \)

\( \text{rm} \)
Compartmentalization micro-policy

Given:

- A linear return capability
- Invariant: at most one return capability per call stack level

Diagram:

- Memory:
  - Jal r
  - ...@EntryPoint
  - Store ra -> *rm
  - Load *rm -> ra
  - Jump ra

- Registers:
  - pc
  - ra
  - rm

Additionally:

- ...
Compartmentalization micro-policy

invariant: at most one return capability per call stack level
Compartmentalization micro-policy

**Invariant:**
At most one return capability per call stack level.

- **Jal r**
  - ...@EntryPoint
  - Store \( r_a \rightarrow *r_m \)
  - Load \( *r_m \rightarrow r_a \)
  - Jump \( r_a \)

**Registers:**
- \( pc \)
- \( r_a \)
- \( r_m \)

**Memory:**
- Linear return capability
  - \( @Ret n \)

**Cross-component return:**
Allowed only via return capability.
Secure compartmentalizing compilation (SCC)

∀ compromise scenarios.

∀ low-level attack from compromised $C_2 \downarrow, C_4 \downarrow, C_5 \downarrow$

∃ high-level attack from some fully defined $A_2, A_4, A_5$

follows from “structured full abstraction for unsafe languages” + “separate compilation”

[Beyond Good and Evil, Juglaret, Hritcu, et al, CSF’16]
Protecting higher-level abstractions

• ML abstractions we want to enforce with micro-policies
  – types, value immutability, opaqueness of closures, parametricity (dynamic sealing), GC vs malloc/free, ...

• F*: enforcing full specifications using micro-policies
  – some can be turned into contracts, checked dynamically
  – fully abstract compilation of F* to ML trivial for ML interfaces (because F* allows and tracks effects, as opposed to Coq)

• Limits of purely-dynamic enforcement
  – functional purity, termination, relational reasoning
  – push these limits further and combine with static analysis
SECOMP focused on dynamic enforcement
but static analysis could help too

• Improving efficiency
  – removing spurious checks
  – just that by using micro-policies our compilers add few explicit checks
  – e.g. turn off memory safety checking for a statically memory safe component that never sends or receives pointers

• Improving transparency
  – allowing more safe behaviors
  – e.g. we could statically detect which copy of the linear return capability the code will use to return (in this case static analysis untrusted)
Micro-policies: remaining fundamental challenges

• Micro-policies for C and ML
  – needed for vertical compiler composition
  – will put micro-policies in the hands of programmers

• Secure micro-policy composition
  – micro-policies are \textit{interferent} reference monitors
  – one micro-policy’s behavior can break another’s guarantees
    • e.g. composing anything with IFC can leak
Beyond full abstraction

• Is full abstraction always the right notion of secure compilation? The right attacker model?

• **Similar properties**
  – secure compartmentalizing compilation (SCC)
  – preservation of hyper-safety properties [Garg et al.]

• **Strictly weaker properties** (easier to enforce!):
  – robust compilation (integrity but no confidentiality)

• **Orthogonal properties**:
  – memory safety (enforcing CompCert memory model)
What secure compilation adds over compositional compiler correctness

• **mapping back arbitrary low-level contexts**
• **preserving integrity properties**
  – robust compilation phrased in terms of this
• **preserving confidentiality properties**
  – full abstraction and preservation of hyper-safety phrased in terms of this
• **stronger notion of components and interfaces**
  – secure compartmentalizing compilation adds this
Verification and testing

• So far all secure compilation work on paper
  – but one can’t verify an interesting compiler on paper
• SECOMP will use proof assistants: Coq and F*
• Reduce effort
  – better automation (e.g. based on SMT like in F*)
  – integrate testing and proving (QuickChick and Luck)
• Problems not just with effort/scale
  – devising good proof techniques for full abstraction
    is a hot research topic of it’s own
SECOMP in a nutshell

• We need more secure languages, compilers, hardware
• Key enabler: micro-policies (software-hardware protection)
• Grand challenge: the first efficient formally secure compilers for realistic programming languages (C, ML, F*)
• Answering challenging fundamental questions
  – attacker models, proof techniques
  – secure composition, micro-policies for C and ML
• Achieving strong security properties like full abstraction
  + testing and proving formally that this is the case
• Measuring & lowering the cost of secure compilation
• Most of this is vaporware at this point but ...
  – building a community, looking for collaborators, and hiring
    ... in order to try to make some of this real
• Looking for excellent interns, PhD students, PostDocs, starting researchers, and engineers

• Prosecco can also support outstanding candidates in the CR2 competition
Collaborators & Community

• Current collaborators from Micro-Policies project
  – UPenn, MIT, Portland State, Draper Labs

• Looking for additional collaborators
  – Several other researchers working on secure compilation
    • Deepak Garg (MPI-SWS), Frank Piessens (KU Leuven),
      Amal Ahmed (Northeastern), Cedric Fournet & Nik Swamy (MSR)
    – Amal Ahmed coming to Paris for 1 year sabbatical (from 09/2017)

• Secure compilation meetings (very informal)
  – 1\textsuperscript{st} at INRIA Paris on August 2016
  – 2\textsuperscript{nd} in Paris on 15(?) January 2017 ... maybe at UPMC
  – build larger research community, identify open problems,
    bring together communities (hardware, systems, security,
    languages, verification, ...)


Questions for Gallium

• What do you think? Is this plan outrageous?

• Would CompCert be a good base for some of this?

• Is there any plan for a RISC-V backend for CompCert?

• Is anyone from Gallium interested in working on secure compilation?