SECOMP

Efficient Formally Secure Compilers to a Tagged Architecture

Cătălin Hrițcu

Prosecco team
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5 year vision
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5 year vision

new grant
Computers are insecure

- devastating low-level vulnerabilities
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
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- programming languages, compilers, and hardware architectures
  - designed in an era of scarce hardware resources
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- 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!
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• Manufacturers have started looking for solutions
  – 2015: Intel Memory Protection Extensions (MPX)
    and Intel Software Guard Extensions (SGX)
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“Spending silicon to improve security”
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
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[PATCH] CVE-2015-7547 --- glibc getaddrinfo() stack-based buffer overflow

• From: "Carlos O'Donell" <carlos at redhat dot com>
• To: GNU C Library <libc-alpha at sourceware dot org>
• Date: Tue, 16 Feb 2016 09:09:52 -0500
• Subject: [PATCH] CVE-2015-7547 --- glibc getaddrinfo() stack-based buffer overflow
• Authentication-results: srcceware.org; auth=none
• References: <56C32C20 dot 1070006 at redhat dot com>

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.
Unsafe low-level languages

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Safer high-level languages

- memory safe (at a cost)
Safer high-level languages

• **memory safe** (at a cost)

• **useful abstractions** for writing secure code:
  – GC, type abstraction, modules, immutability, ...
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
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  – unsafe interoperability: all high-level safety guarantees lost

• Today’s languages & compilers plagued by low-level attacks
  – main culprit: 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
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software-defined, hardware-accelerated, tag-based monitoring

```

  pc
  r0
  r1

mem[0]  "store r0 r1"
mem[2]
mem[3]
```
Key enabler: Micro-Policies

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

- pc
- r0
- r1
- tpc
- tr0
- tr1
- "store r0 r1"
- mem[0]
- mem[2]
- mem[3]
- tm0
- tm1
- tm2
- tm3
Key enabler: Micro-Policies
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\[
\begin{array}{|c|c|}
\hline
pc & tpc \\
\hline
r0 & tr0 \\
\hline
r1 & tr1 \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|}
\hline
mem[0] & tm0 \\
\hline
“store r0 r1” & tm1 \\
\hline
mem[2] & tm2 \\
\hline
mem[3] & tm3 \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|c|c|}
\hline
tpc & tr0 & tr1 & tm3 & tm1 \\
\hline
\end{array}
\]

store

monitor
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>tm1</td>
<td></td>
</tr>
<tr>
<td>mem[2]</td>
<td></td>
</tr>
<tr>
<td>tm2</td>
<td></td>
</tr>
<tr>
<td>mem[3]</td>
<td></td>
</tr>
<tr>
<td>tm3</td>
<td></td>
</tr>
</tbody>
</table>

```
store r0 r1
```

monitor

store

allow

```
tpc’
tm3’
```
Key enabler: Micro-Policies
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<table>
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<tr>
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<tbody>
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</tr>
<tr>
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<th>tm0</th>
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<tbody>
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</tr>
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<td>tm2</td>
</tr>
<tr>
<td>mem[3]</td>
<td>tm3’</td>
</tr>
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</table>

store

monitor

allow

\[ \text{tpc} \quad \text{tr0} \quad \text{tr1} = \text{tm3} \quad \text{tm1} \]
Key enabler: Micro-Policies
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```
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<td>tm3'</td>
</tr>
</tbody>
</table>
```

```
store
```

```
Opcode: "store r0 r1"
```

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

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

\[
\begin{array}{c|c|c|c|c}
   \text{pc} & \text{tpc} & \text{mem[0]} & \text{tm0} \\
   \text{r0} & \text{tr0} & \text{“store r0 r1”} & \text{tm1} \\
   \text{r1} & \text{tr1} & \text{mem[2]} & \text{tm2} \\
   & & \text{mem[3]} & \text{tm3} \\
\end{array}
\]

\[\text{store r0 r1} \neq \text{tm3} \Rightarrow \text{tm1} \]

\[\text{policy violation stopped! (e.g. out of bounds write)}\]
Micro-policies are cool!

- **low level + fine grained**: unbounded per-word metadata, checked & propagated on each instruction
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
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DRAPER  bluespec®
Expressiveness

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

...
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Verified (in Coq)  
[POPL’14]  
[Oakland’15]
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• heap memory safety
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Verified (in Coq)

Evaluated (<10% runtime overhead)
SECOMP grand challenge

Use micro-policies to build the first efficient formally secure compilers for realistic programming languages
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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
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* = ML + verification]
Formally verify: full abstraction

holy grail of secure compilation, enforcing abstractions all the way down
Formally verify: **full abstraction**

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

- program behavior
- compiler correctness (e.g. CompCert)
- not enough

![Diagram]

- source component
- target component
- low-level attacker
- e.g. arbitrary machine code
Formally verify: full abstraction

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

- program behavior
- compiler correctness (e.g. CompCert) not enough
- program behavior

source component ➔ high-level attacker ➔ target component ➔ low-level attacker

- compiler ➔ full abstraction ➔ e.g. arbitrary machine code
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

full abstraction

target component

protected

low-level attacker

no extra power

e.g. arbitrary machine code

not enough

not enough

full abstraction

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

holy 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

$\exists$ low-level attacker

$1^{st}$ high-level component

compiler

$1^{st}$ compiled component

$\exists$ low-level attacker
Fully abstract compilation, definition

∃ low-level attacker.

1\textsuperscript{st} high-level component

\hspace{2cm}

compiler

\hspace{2cm}

1\textsuperscript{st} compiled component

\hspace{2cm}

\rightarrow

\hspace{2cm}

low-level attacker

\hspace{2cm}

2\textsuperscript{nd} high-level component

\hspace{2cm}

\rightarrow

\hspace{2cm}

compiler

\hspace{2cm}

2\textsuperscript{nd} compiled component

\hspace{2cm}

\rightarrow

\hspace{2cm}

\sim

\hspace{2cm}

\rightarrow

\hspace{2cm}

low-level attacker
Fully abstract compilation, definition

∃ high-level attacker

 compiler

 1st high-level component ←→ high-level attacker

 1st compiled component ←→ low-level attacker

∃ low-level attacker

 compiler

 2nd high-level component ←→ high-level attacker

 2nd compiled component ←→ low-level attacker

∃ compiler

⇒

¬
Fully abstract compilation, definition

∃ high-level attacker.

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

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

∃ low-level attacker.

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

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

F* language (ML + verification)

C language
+ memory safety
+ components
SECOMP: achieving full abstraction at scale

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Diagram:

```
miTLS*  
SecF* +  
SecML    
      memory safe C component
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- **ASM language**
  (RISC-V + micro-policies)
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  + components

- **ASM language**
  (RISC-V + micro-policies)

Diagram showing the components and their interactions:

- miTLS*
- SecF* + SecML
- CompSec*
- memory safe C component
- legacy C component
- CompSec
- ASM component

Protecting component boundaries
SECOMP: achieving full abstraction at scale

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protecting higher-level abstractions

protecting component boundaries

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Protecting component boundaries

• Add mutually distrustful components to C
  – interacting only via **strictly enforced interfaces**
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• CompSec compiler chain (based on CompCert)
  – propagate interface information to produced binary
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• Micro-policy simultaneously enforcing
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  – type-safe procedure call and return discipline
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• Interesting attacker model
  – extending full abs. to mutual distrust + unsafe source
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Recent preliminary work, joint with Yannis Jougaret et al
Compartmentalization micro-policy

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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 $r_a$

C₁

C₂

registers

linear return capability

@Ret n

@Ret n

 @(n+1)

pc $r_a \ r_m$

17
Compartmentalization micro-policy

memory

C_1

Jal r
...
...
...@EntryPoint
Store r_a \rightarrow \star r_m
...
Load \star r_m \rightarrow r_a
Jump r_a

C_2

C_1

C_2

registers

\textbf{invariant:}
at most one return capability per call stack level

load target register into base register

PC register

linear return capability

\@Ret n

\@Ret n

\@(n+1)
Compartmentalization micro-policy

memory

Jal r
...
...
...@EntryPoint
Store ra \rightarrow *rm
...
Load *rm \rightarrow ra
Jump ra

registers

@Ret n

pc ra rm

invariant:
at most one return capability per call stack level

linear return capability

@((n+1))
Compartmentalization micro-policy

memory

Jal r
...
...
...@EntryPoint
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...
Load $\star r_m \rightarrow r_a$
Jump $r_a$

registers

invariant:
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linear return capability

@Ret n

cross-component return only allowed via return capability

$n+1$

pc $\quad r_a \quad r_m$
Secure compartmentalizing compilation (SCC)

∀ compromise scenarios.
Secure compartmentalizing compilation (SCC)

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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 $A_2, A_4, A_5$
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, ...
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  – functional purity, termination, relational reasoning
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• 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
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
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• Micro-policies for C and ML
  – needed for vertical compiler composition
  – will put micro-policies in the hands of programmers
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remaining fundamental challenges

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  – needed for vertical compiler composition
  – will put micro-policies in the hands of programmers

• **Secure micro-policy composition**
  – micro-policies are *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?
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• **Similar properties**
  – secure compartmentalizing compilation (SCC)
  – preservation of hyper-safety properties [Garg et al.]
Beyond full abstraction

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

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• 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)
Verification and testing

• So far all secure compilation work on paper
  – but one can’t verify an interesting compiler on paper

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  – 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
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- Key enabler: **micro-policies** (software-hardware protection)
- Grand challenge: **the first efficient formally secure compilers**
  for realistic programming languages (C, ML, F*)
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• 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
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• 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)
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• Secure compilation meetings (very informal)
  – 1st at INRIA Paris on August 2016
  – 2nd 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?