Porting Software to CHERI

Cybersecurity by design - from research to industry
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Today’s talk

What does it even mean to port software to CHERI?

What kinds of changes are required and how much effort does that involve?

And when I do all this what is achieved?

What does it even mean to port software to CHERI?

“**porting** is the process of adapting **software** for the purpose of achieving some form of execution in a computing environment

… the term "port" is derived from the Latin portare, meaning "to carry". When code is not compatible with a particular operating system [*or language*] or architecture, the code must be "carried" [or "ported"] to the new system.”

- Wikipedia, Porting [Software Engineering]

Porting to Memory Safe languages

"70% of security vulnerabilities that Microsoft fixes and assigns a CVEs are due to memory safety issues. This is despite mitigations including intense code review, training, static analysis, and more."

https://msrc.microsoft.com/blog/2019/07/we-need-a-safer-systems-programming-language/

Programming language	Approximate LoC (Open Source projects)	Memory safety	Memory safety with CHERI
C	10,000,000,000	✗	✚
C++	3,000,000,000	✗	✚
Rust	40,000,000	✚	✚ ✚

Synopsys Black Duck Open Hub: https://www.openhub.net/languages?query=rust&sort=code

Porting to CHERI

For this talk we are focussed on aspects of porting related to the CHERI architecture.

- And specifically porting legacy C/C++ codebases.

Design goals:

1. C programmers should be able to port existing C code bases with minimal effort.
2. Existing compiler infrastructure and optimisations should require only limited changes.
3. Memory-safety errors that can lead to exploitable vulnerabilities should be mitigated where possible.

Conventional architecture C/C++

```
unsigned long long
incrementInteger(unsigned long long num) {
    return num + 1;
}

char*
incrementPointer(char* ptr) {
    return ptr + 1;
}
```

```
incrementInteger(unsigned long long):
        sub     sp, sp, #16
        str     x0, [sp, 8]
        ldr     x0, [sp, 8]
        add     x0, x0, 1
        add     sp, sp, 16
        ret

incrementPointer(char*):
        sub     sp, sp, #16
        str     x0, [sp, 8]
        ldr     x0, [sp, 8]
        add     x0, x0, 1
        add     sp, sp, 16
        ret
```

Conventional C: Pointers represented with simple machine-word integers

https://godbolt.org/

What is CHERI C/C++?

```
unsigned long long
incrementInteger(unsigned long long num) {
   return num + 1;
}

char*
incrementPointer(char* ptr) {
   return ptr + 1;
}
```

```
incrementInteger(unsigned long long):
      sub   csp, csp, #16
      str   x0, [csp, #8]
      ldr   x8, [csp, #8]
      add   x0, x8, #1
      add   csp, csp, #16
      ret   c30

incrementPointer(char*):
      sub   csp, csp, #16
      str   c0, [csp, #0]
      ldr   c0, [csp, #0]
      add   c0, c0, #1
      add   csp, csp, #16
      ret   c30
```

“Pointer arithmetic is implemented as arithmetic over these capabilities”

“Basic idea is to represent all C source-language pointers with machine capabilities, instead of machine words” https://github.com/chromium-cheri/chromium/commit/a39b2fe1f1e2c4a84c68aa9045637f39fccd6f16#diff-6d5f6348e30b4627ecd30be810c82c394d27e0877483789de3a497416f99a151R25

Representation of C language pointers with capabilities

```
struct DataOrder {
 DataType type;
 uint64_t value;
};
```

→

```
struct DataOrder {
 DataType type;
 uintptr_t value;
};
```

Modify type usage to ensure pointer and integer values are distinct

What can programmers rely on and what they are required to ensure, for well defined CHERI C/C++?

In the presence of compiler optimisations, this can be complex

However, in practice most things that programmers are required to do is straightforward following a set of common porting tasks:

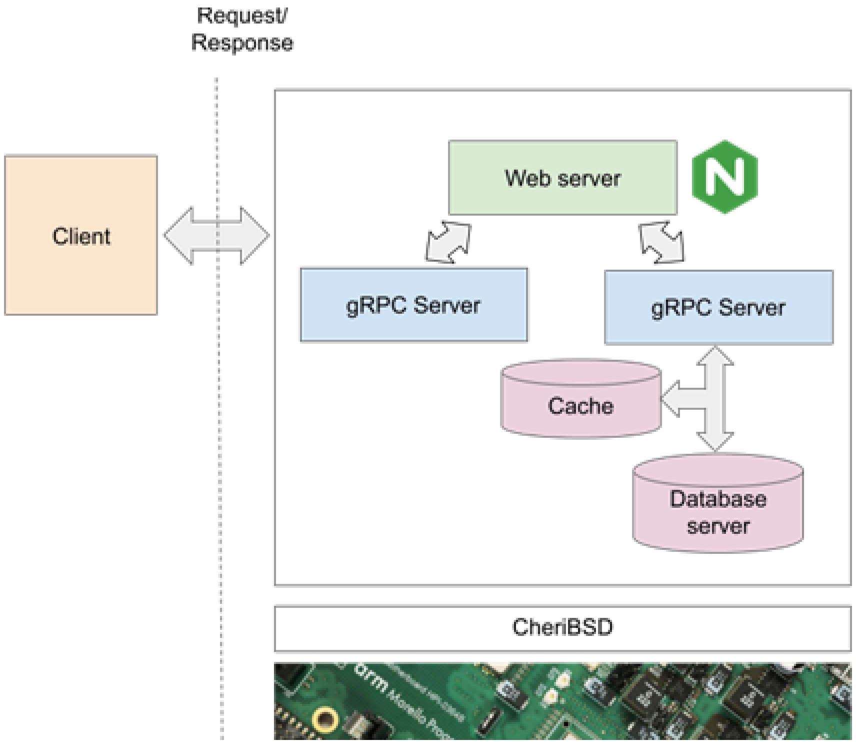
See CHERI C/C++ programming guide: https://www.cl.cam.ac.uk/techreports/UCAM-CL-TR-947.pdf

Example nginx web server

A web server accepts requests via HTTP or its secure variant HTTPS. A user agent, commonly a web browser, initiates communication by making a request for a resource, and the server responds with the content or an error.

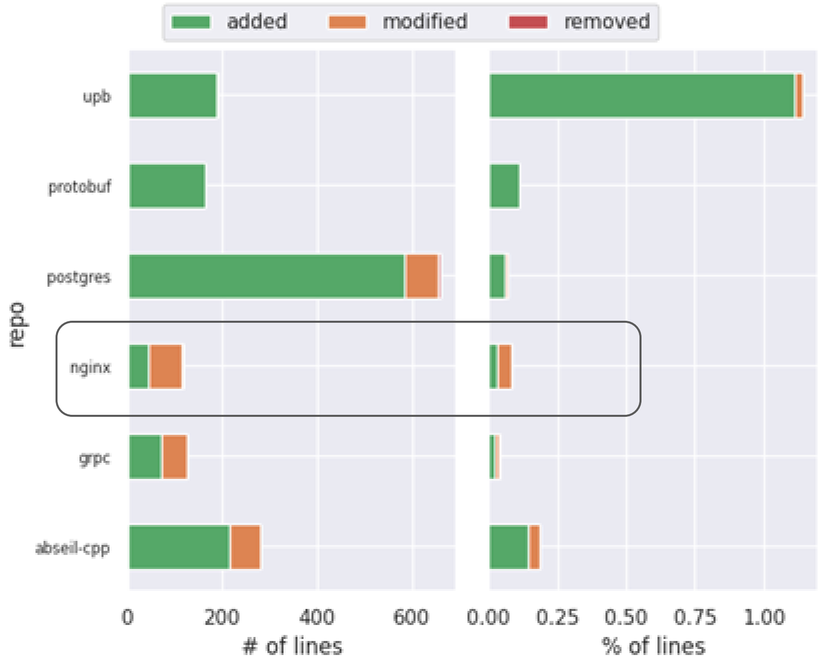
nginx is currently most deployed web server accounting for 34.1%; can also be deployed as a reverse proxy, load balancer, mail proxy and HTTP cache.

Approximately 140k lines of C code.



How much effort does that involve?

- %SLoc changed in nginx port approximately 0.10%
- Consistent with other recent studies with %SLoC changes typically 0.10%-0.25%
- Limitations:
  - The nginx port is fairly mature, but further issues may arise with testing.
  - nginx memory allocators must be modified to obtain the full benefits of CHERI spatial memory protection.
  - Modifications to support sub-object bounds are missing from these estimates.



Project	Total SLoC	Changed SLoC	% Changed SLoC	Total files	Changed files	% Changed files
nginx w/o tests	139804	118	0.10	337	20	5.90

Sliding scale of Effort

Non effort (0%)

Desktop stack - Plasma-framework, Dolphin,

- Modern C/C++ usage across code base
- Use of C++ where templating reduces us of integer/pointer conversions
- High-level applications, rather than low-level software

Minimal/small effort (0.10-0.25%)

Web service stack - nginx, Postgres, protobuf

High-effort (1-2%)

Operating system kernels - FreeBSD

Language runtimes - v8 Javascript runtime

- Modern C/C++ usage
- Misuse of standard types
- Complex memory allocators
- Internal Memory models

What is achieved?

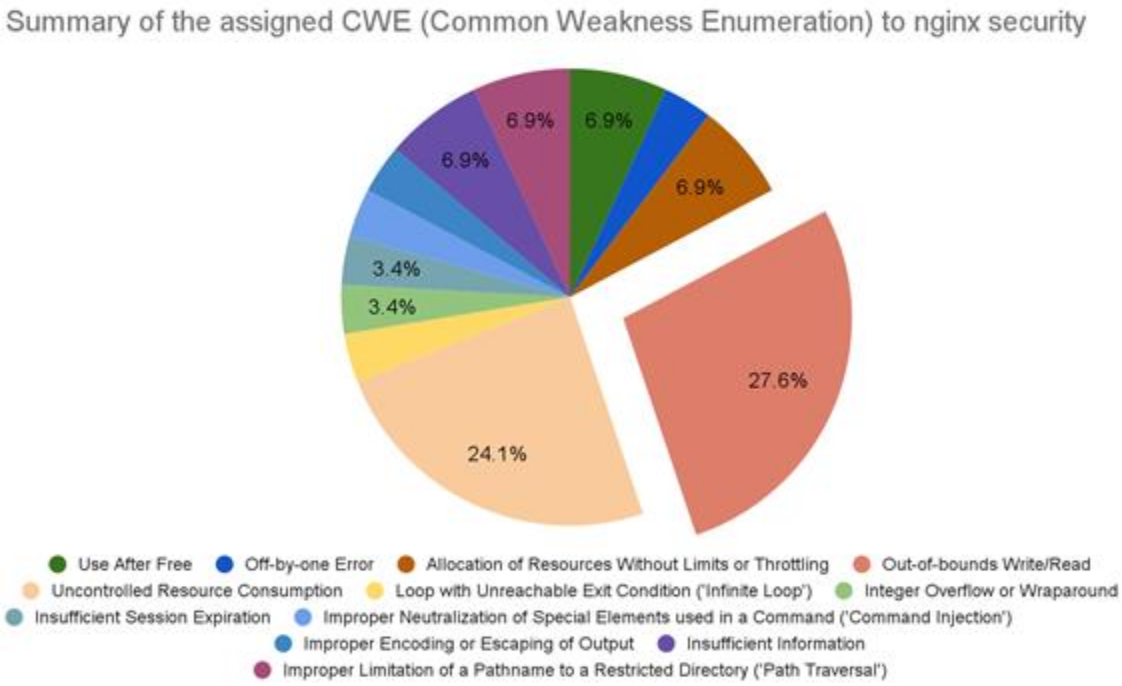
Threat model:

- Remote code execution
- Private data disclosure
- Denial of service

Analytical study analysing historic vulnerabilities

Approximately 28% of CWEs assigned to nginx security advisories relate to buffer overwrites and overreads

Uncontrolled resource consumption is the second largest weakness



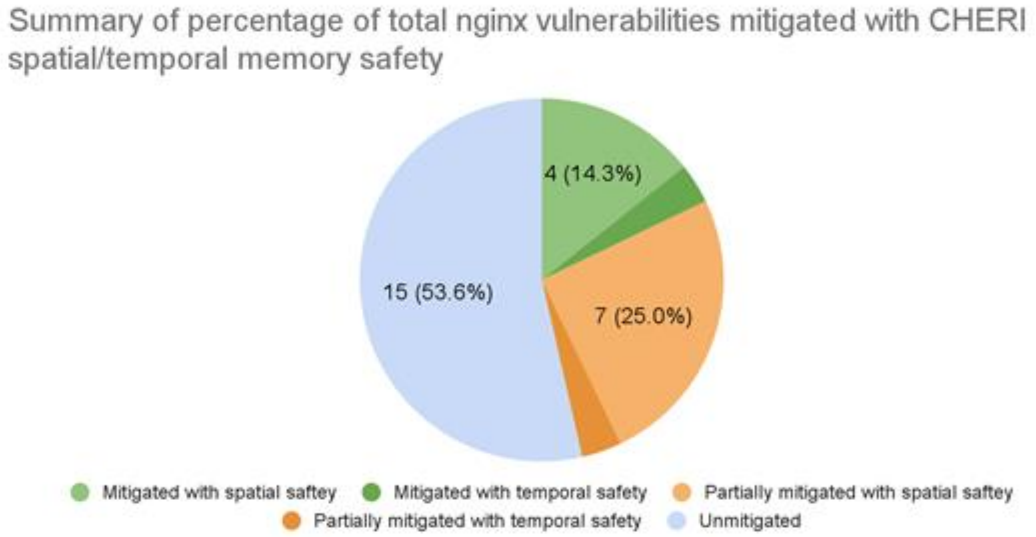
What is achieved?

CHERI protections have been shown to mitigate ~60-70% of memory safety vulnerabilities

- Memory safety issues accounting for around 70% of the total vulnerabilities

Mitigation rate of security vulnerabilities in nginx with CHERI spatial/temporal memory protection is approximately 46%

Applying compartmentalisation to nginx modules improves the potential total mitigation rate to 61%



Q&A

What does it even mean to port software to CHERI?

Porting to CHERI C/C++.

What kinds of changes are required and how much effort does that involve?

Typically in the region of 0.1-0.25%; larger for some classes of software.

And when I do all this what is achieved?

Deterministic mitigation of approximately 60-70% of memory safety issues.