CTSRD

CRASH-worthy
Trustworthy
Systems
Research and
Development

The CHERI CPU

RISC in the age of risk

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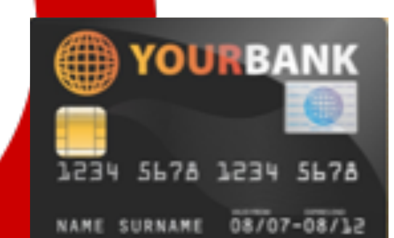
Memory: You’re doing it wrong!

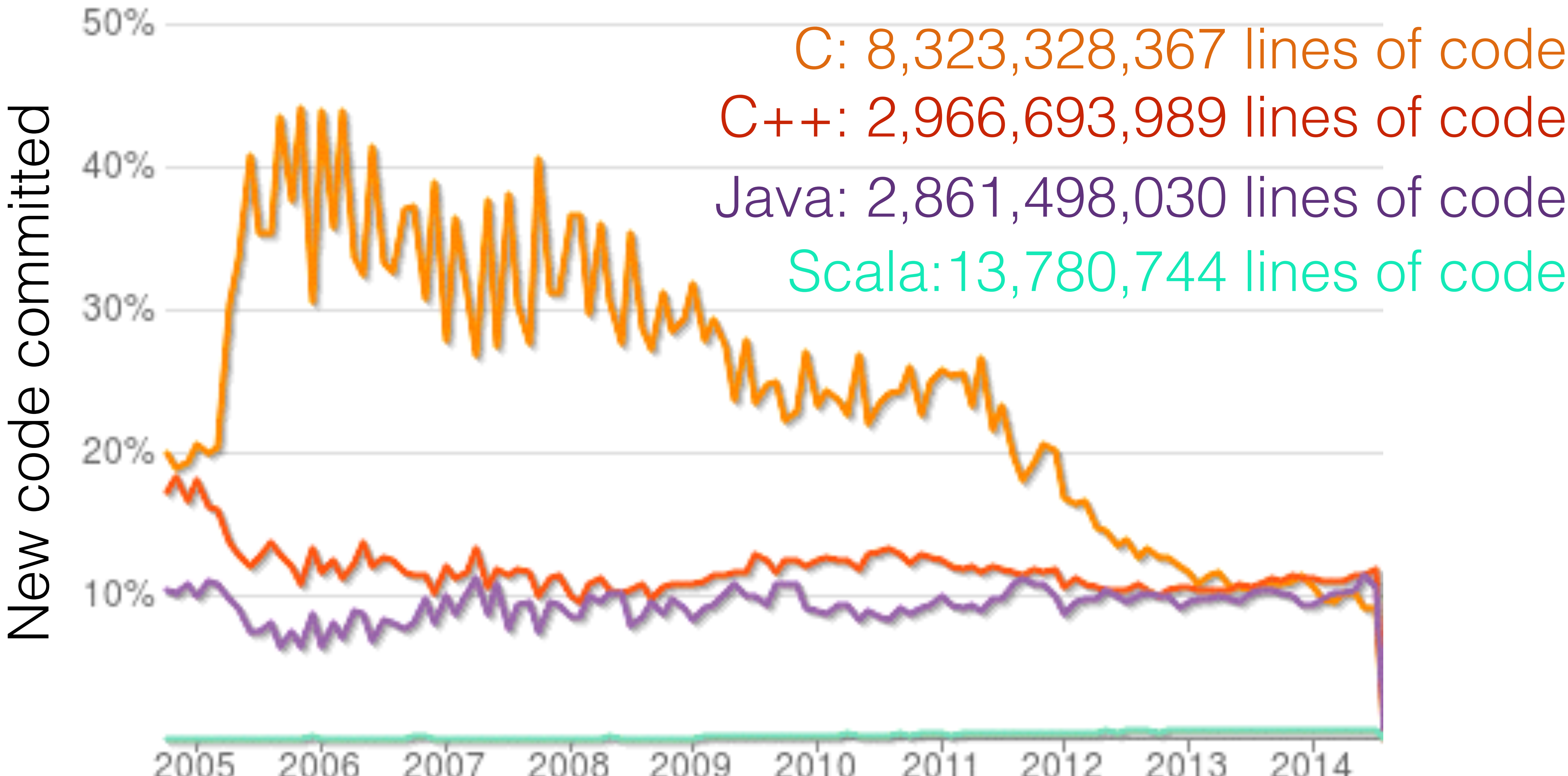
TARGET



~82% of exploited vulnerabilities in 2012

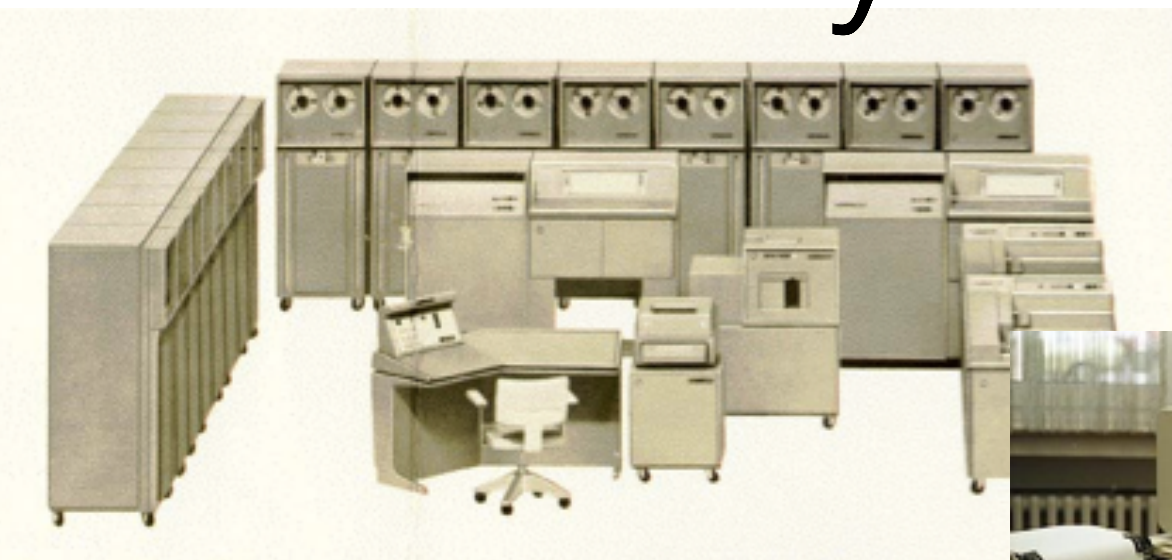
— Software Vulnerability Exploitation Trends, Microsoft

Low-level languages rule



Source: openhub.net

Security is important again



Multi-user systems

Disconnected single-user systems

Single-user, multi-attacker systems

RISC is for compilers

- Nothing that can be done fast in software should be done in hardware.
- Everything that can only be done well in hardware should be in hardware.

The CHERI model

- Memory protection as a first-class part of the ISA
- A single abstraction for bounds checking and sandboxing
- Mechanism in the hardware, policy in software

Pointers should be capabilities

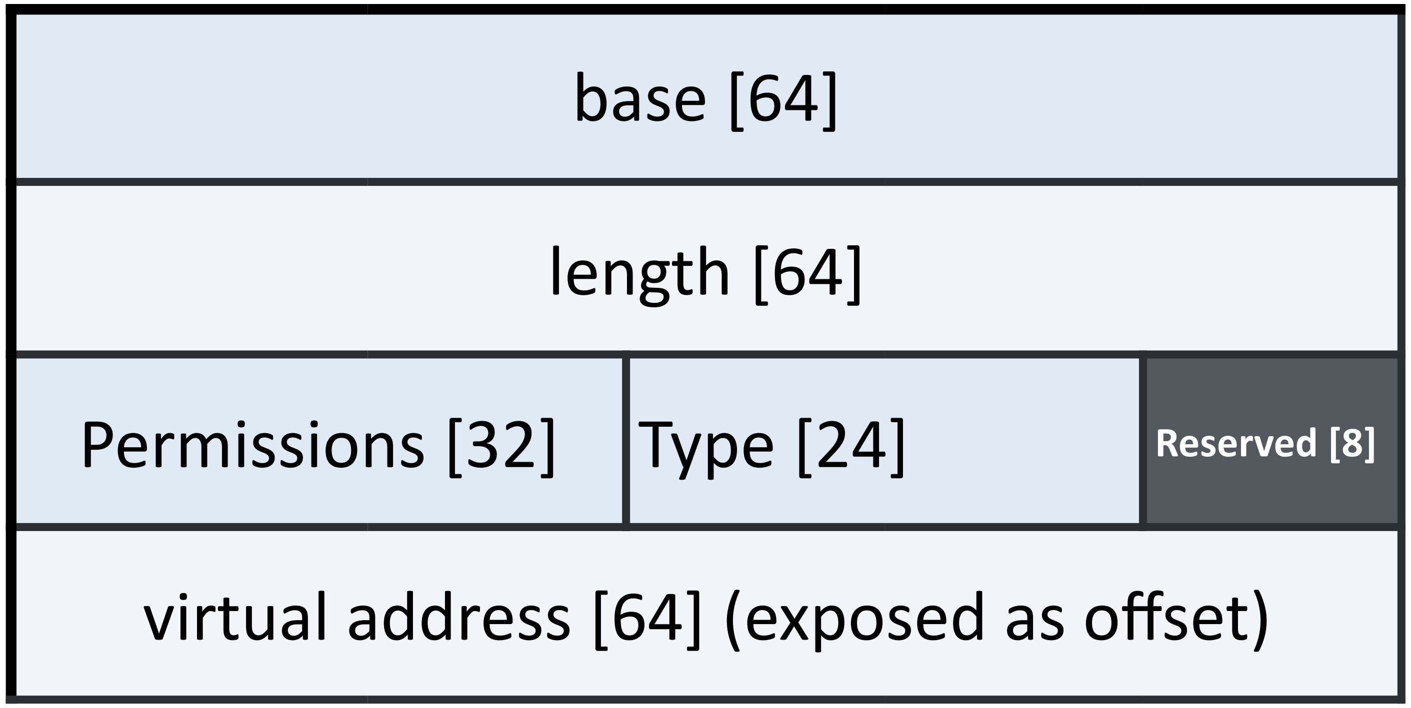
- Smalltalk (Java, etc) pointers confer the rights to access an object.
- C pointers can (in practice) be constructed from arbitrary integers.
- Capabilities are *unforgeable tokens of authority.*

CHERI capabilities

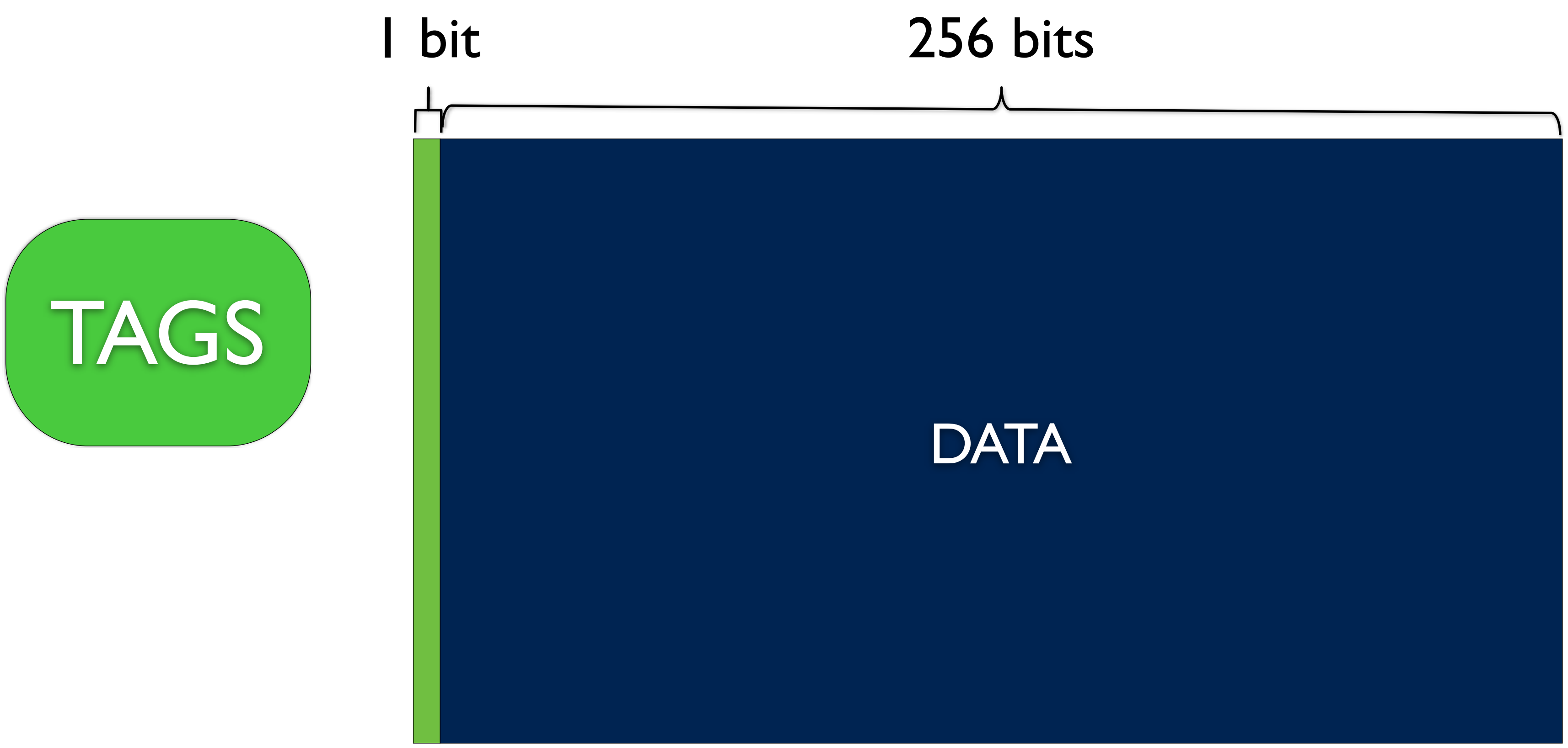
ISA Operations

Field	Operation
Permissions	Bitwise and
Base	Increment (and decrease length)
Length	Decrease
Offset	Arbitrary manipulation

32 capability registers

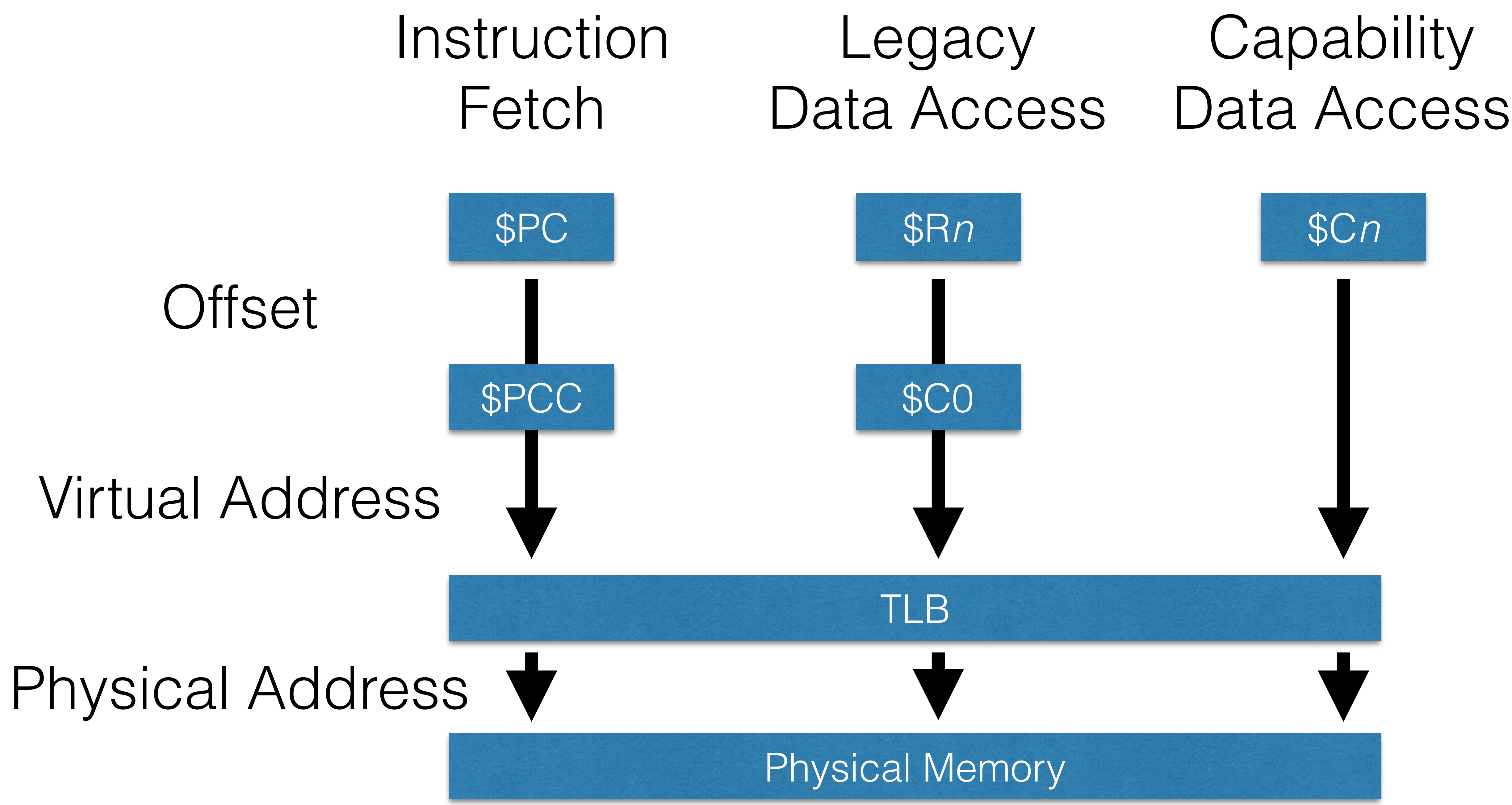


Tags to Protect Capabilities in Memory

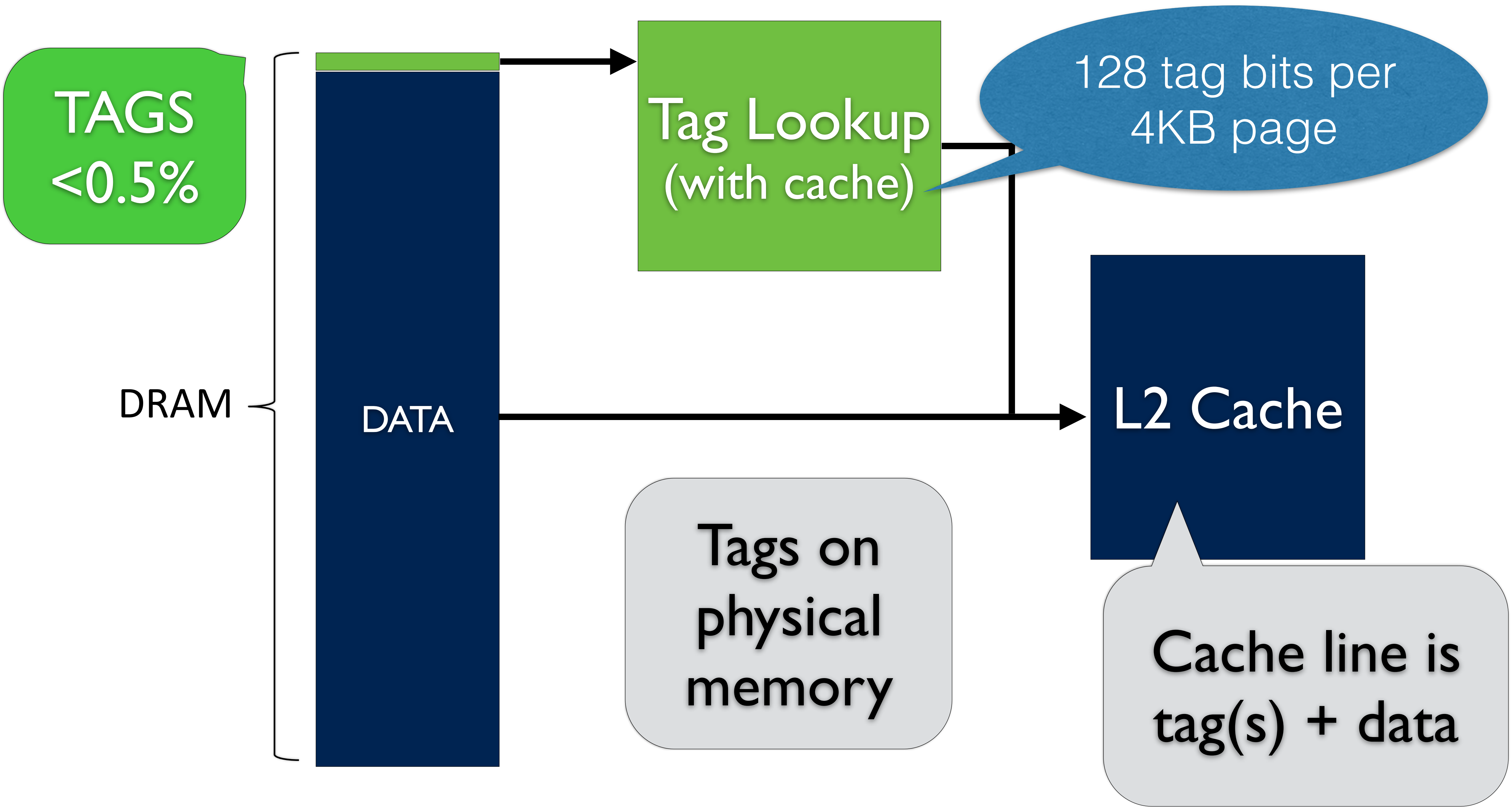


Capabilities on the stack and in data structures

Address Calculation



Tag Table in Commodity DRAM



Paged Memory

- OS managed
- Enables swapping
- Centralised
- Allows revocation

Address validation

Capabilities

- Compiler managed
- Precise
- Can be delegated
- Many domains

Pointer safety

Paged Memory + Capabilities

- OS managed
- Enables swapping
- Centralised
- Allows revocation

Address validation

- Compiler managed
- Precise
- Can be delegated
- Many domains

Pointer safety

CHERI

Memory safety in hardware

- All memory accesses must be via a valid capability
- Instructions only allow restricting range / permissions of capabilities
- Now all we need is software…

Building on open source

- A full open source stack:
  - LLVM/Clang-based compiler.
  - Modified FreeBSD.
  - Extended BERI processor.
  - Real software from the FreeBSD ports collection.

Process start

- `$c0` and `$pcc` cover the entire address space.
- Unmodified code is completely oblivious.
- CHERI-aware code can derive restricted capabilities from either.
- Compartments can be created by discarding/subsetting `$c0` in some threads.

Don’t break the world!

- Code that doesn’t contain memory safety errors should work!
- Even if it does slightly (or very) evil things with pointers!
- Ideally only code with memory safety errors should break.

C is weird

- Long standard describes allowed behaviour.
- Lots of things are *implementation defined* or *undefined*.
- **All** nontrivial programs depend on implementation-defined behaviour.
- Breaking this makes programmers cranky!
- We discovered most of these things when we broke them and tried to compile real programs (e.g. tcpdump)

Pointers and Integers

7.20.1.4 Integer types capable of holding object pointers

The following type designates a signed integer type with the property that any valid pointer to **void** can be converted to this type, then converted back to pointer to **void**, and the result will compare equal to the original pointer:

intptr_t

The following type designates an unsigned integer type with the property that any valid pointer to **void** can be converted to this type, then converted back to pointer to **void**, and the result will compare equal to the original pointer:

uintptr_t

These types are optional.

```
void *a = something();
intptr_t b = (intptr_t)a;
a = (void*)b;
```

Implementation defined!

```
void *a = something();
long long b = (long long)a;
a = (void*)b;
```

Simple Problem: `memcpy()`

```
struct foo {
    void *a;
    int   b;
};
struct foo new = old;
```

```
memcpy(&new, &old, sizeof(struct foo));
```

The `memcpy()` function doesn't know if it's copying pointers or data!

Pointers as capabilities

C code used `__capability` qualifier to tag pointers to be represented as capabilities

```
// 64-bit integer (address)
void *foo;
// 256-bit capability
__capability int *bar;
// Increment offset by sizeof(int)
bar++;
// Load 4 bytes at offset+sizeof(int)
bar[1];
```

Enabling pointer abuse

```
// The low bit of a sensibly aligned pointer is
// always 0, so we can hide a flag in it
__capability int *set_flag(__capability int *b)
{
  return (__capability int*)((__intcap_t)b | 1);
}
```

Enabling pointer abuse

```
# Integer constant 1
daddiu $1, $zero, 1
# Derive a canonical null capability
cfromptr $c1, $c0, $zero
# Set intcap_t (tag not valid) to 1
csetoffset $c1, $c1, $1
# Get the integer values of both operands
cgetoffset $1, $c1
cgetoffset $2, $c3
# Perform the arithmetic
or $1, $1, $2
# Set the offset in the original capability
csetoffset $c3, $c3, $1
```

Legacy interoperability
(is hard)

```
void *foo;
__capability char *bar;
// What does this do?
bar = (__capability char *)foo;
// Or this?
foo = (void *)bar;
```

First cut at Casts

```
# Cast from pointer ($1) to capability ($c1)
CIncBase $c1, $c0, $1
# Cast from capability ($c1) to pointer ($1)
CGetBase $c1, $1
```

- What happens if the pointer is null?
- What happens if the capability is outside the `$c0` range or `$c0` has a non-zero offset?

NULL in C

§6.3.2.3.3:

An integer constant expression with the value 0, or such an expression cast to type **`void *`**, is called a *null pointer constant*.[66]) If a null pointer constant is converted to a pointer type, the resulting pointer, called a *null pointer*, is guaranteed to compare unequal to a pointer to any object or function.

```
void *null = (void*)0;
int a = 0;
void *might_be_null = (void*)a;
```

No C programmer has **ever** paid attention to this!

Casts in CHERI

```
# Cast from pointer ($1) to capability ($c1)
CFromPtr $c1, $c0, $1
# Cast from capability ($c1) to pointer ($1)
CToPtr   $1, $c0, $c1
```

- `CFromPtr` gives a null capability if the integer is 0
- `CToPtr` gives a 0 integer if the capability is null or outside of `$c0`

Where do bounds come from?

- An object in C is a single allocation.
- OpenSSL's Heartbleed vulnerability was caused (partly) by splitting allocations.
- Some programmer policy is essential!
- Sizes of globals, stack allocations, `malloc()` calls are not enough (but they're a good start!)

Safer returning

Capabilities are for code, not just for ~~christmas~~ data

	MIPS	CHERI
Call	`jalr $t9, $ra`	`cjalr $c12, $c17`
Return	`jr $ra`	`cjr $c17`
Spill return address to stack	`sd $ra, 32($sp)`	`csc $c17, $sp, 32($c11)`
Behaviour if spilled value is corrupted	**Jump somewhere (attacker's choice)**	**Trap**

Comparing pointers

- C says it’s undefined behaviour to compare pointers to different objects
- C programmers do it all the time
- CHERI adds pointer compare instructions

Some evil things people do to pointers

- Store them in integer variables (works if they're [u]intcap_t)
- Do arbitrary arithmetic on them
- Let them go out of range in the middle of a calculation
- Compare pointers to different objects

All of these need to work!

A tale of ~~2~~ 3 ABIs

- Incremental deployment is vital for testing
- Rewriting (or even recompiling) all code at once isn't feasible

More compatible | More safe

n64
Pure MIPS

n64 + CHERI
Some pointers are capabilities

Pure-capability
All pointers are capabilities

The pure-capability ABI

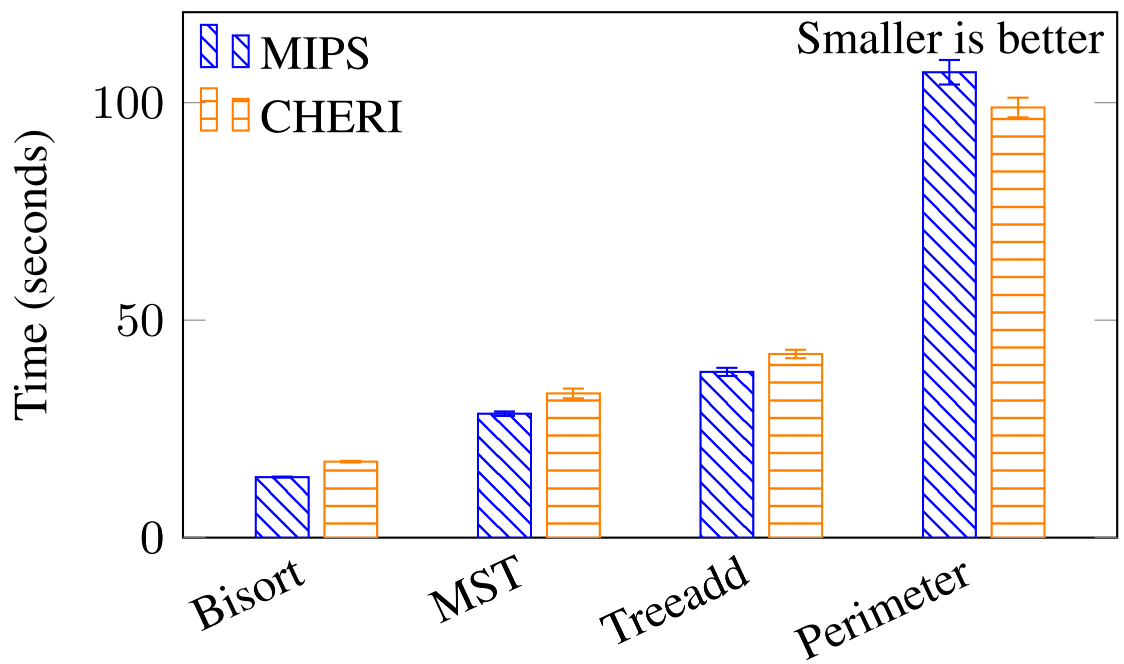
- Code where all pointers are capabilities.
- May have a null `$c0`.
- Can only see a subset of all memory.
- Incompatible with syscall ABI.

CHERI-friendly libraries

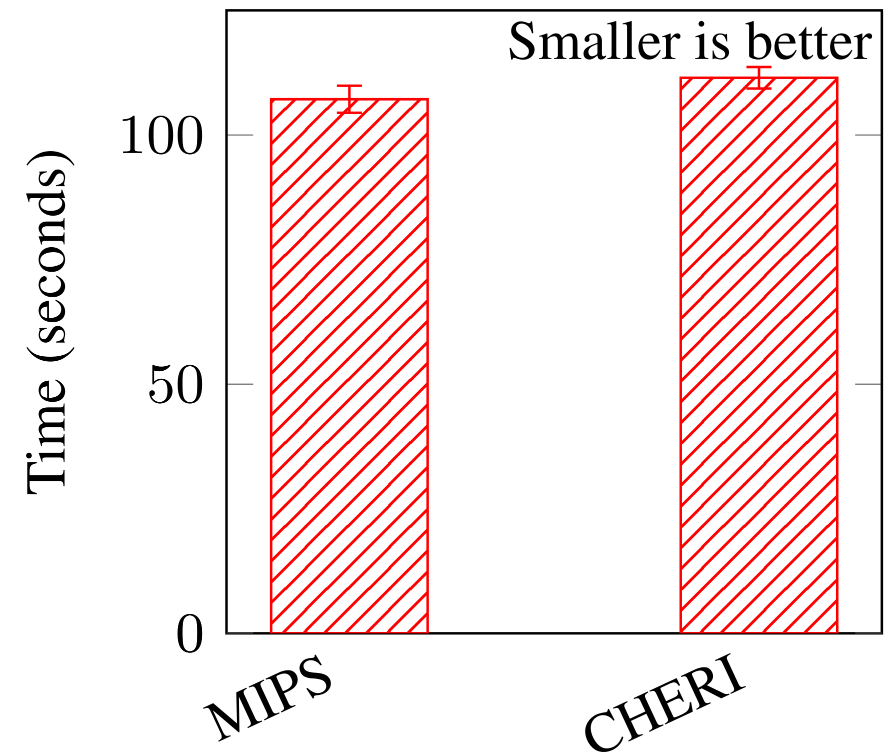
- Always use typedefs for pointer types.
- Don’t put struct definitions for opaque types in headers.
- Separate file-handling layers (that make syscalls) from buffer-handling layers.
- Write good code!

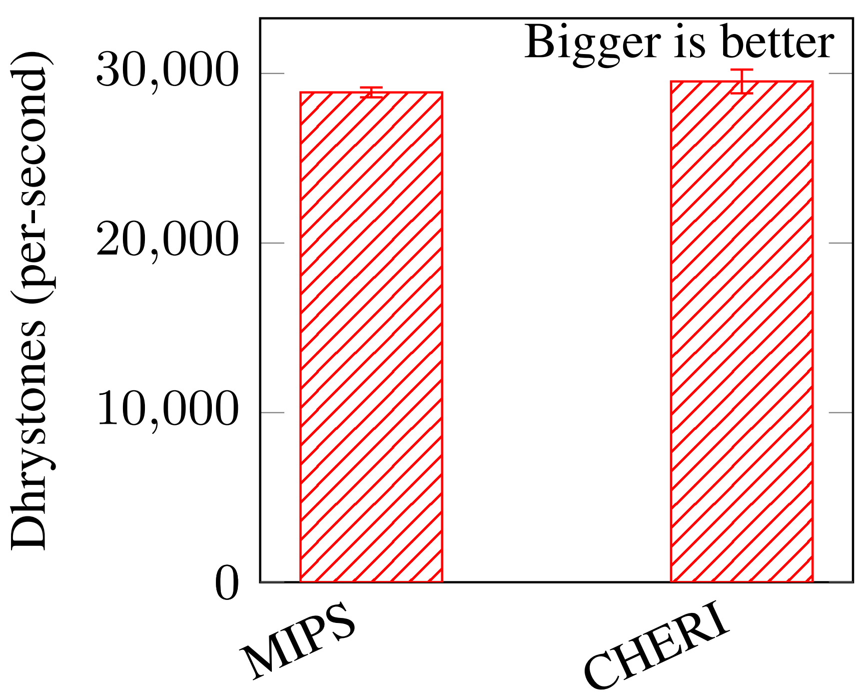
Memory Safety Overhead

Olden (pointer-chasing) benchmarks



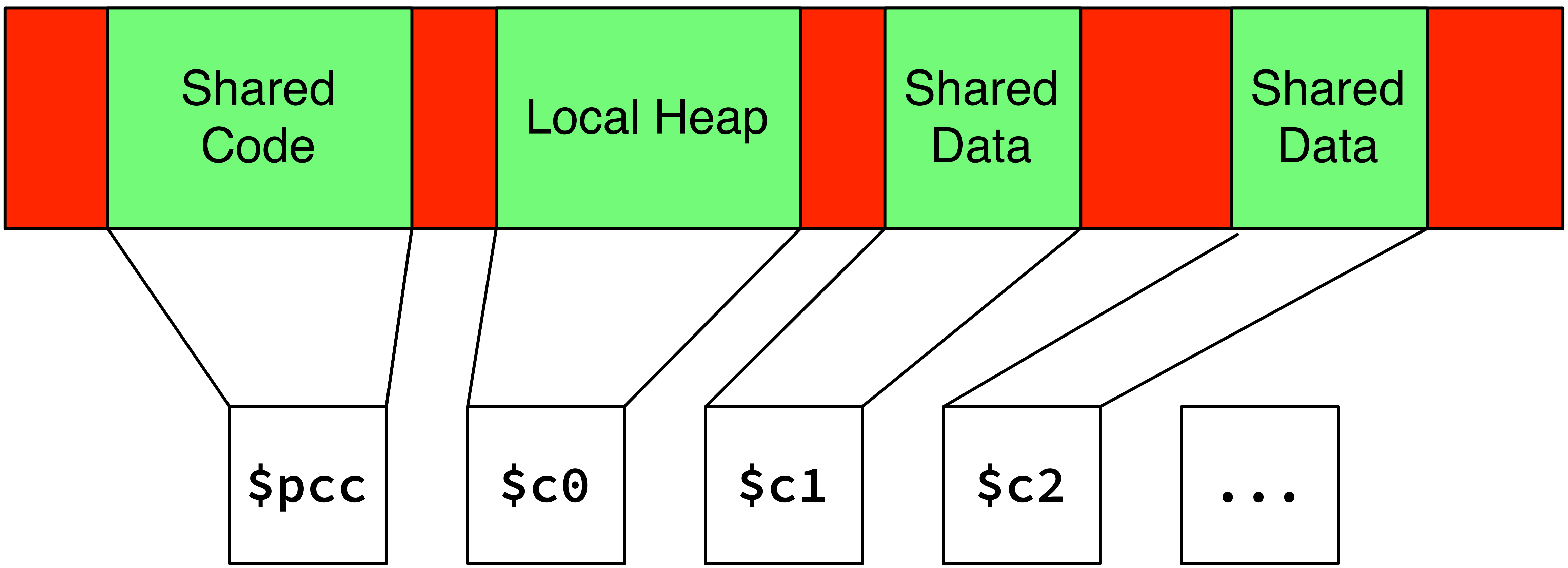
tcpdump (real code!)





Dhrystone (CPU-intensive) benchmark

Building sandboxes



No access to any memory without valid capabilities

Process-based sandboxes?

- More expensive to create (new kernel process, virtual memory map)
- More expensive to share (one TLB entry per page)
- No fine-grained sharing (page granularity)
- Better separation of kernel rights (so far!)

Library Sandboxing

- Private heap per library instance (multiple isolated copies of the same library allowed)
- Shared code between all instances
- Calls to the library delegate access to shared buffers
- Maintaining ABIs can be a bit tricky!

Lessons Learned

Only testing with real code can tell you how useful your ISA really is. Convincing a compiler it's useful is a lot harder than convincing yourself.

Software stack on GitHub now, hardware due new open-source release Real Soon Now™

Further Reading

David Chisnall, Colin Rothwell, Brooks Davis, Robert N.M. Watson, Jonathan Woodruff, Munraj Vadera, Simon W. Moore, Peter G. Neumann and Michael Roe. ***Beyond the PDP-11: Processor support for a memory-safe C abstract machine***. Proceedings of the Fifteenth Edition of ASPLOS on Architectural Support for Programming Languages and Operating Systems, ACM (2015).

Jonathan Woodruff, Robert N.M. Watson, David Chisnall, Simon W. Moore, Jonathan Anderson, Brooks Davis, Ben Laurie, Peter G. Neumann, Robert Norton and Michael Roe. ***The CHERI capability model: revisiting RISC in an age of risk***. ISCA '14: Proceeding of the 41st annual international symposium on Computer architecture, IEEE Press (2014), 457–468.

http://chericpu.org

http://www.cl.cam.ac.uk/research/security/ctsrd/

Thanks to DARPA, AFRL, Google!