CTSRD

CRASH-WORTHY TRUSTWORTHY SYSTEMS RESEARCH AND DEVELOPMENT

CHERI

C/C++-language and compiler support

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CHERI Microkernel Workshop – 23 April 2016

Approved for public release; distribution is unlimited. This research is sponsored by the Defense Advanced Research Projects Agency (DARPA) and the Air Force Research Laboratory (AFRL), under contracts FA8750-10-C-0237 ('CTSRD') and FA8750-11-C-0249 ('MRC2'). The views, opinions, and/or findings contained in this article/presentation are those of the author(s)/presenter(s) and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

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Compatibility vs protection

More secure →

- Unmodified binaries (Legacy ABI)
- Annotated code (Hybrid ABI)
- Pure-capability ABI

← More compatible

Pointer representation:

Integers
Manipulated as data
No tie to objects

Capabilities
Bounds checked
Permissions enforced
Protected by tag

Why capabilities for pointers?

```
int foo[32];
union
{
    int *a;
    int b;
} un;

foo[32] = 12; // Bound violation, run-time trap
un.b = 12;
un.a[0]; // Tag violation, run-time trap
```

- Tags allow pointers to be identified for accurate garbage collection
- Memory protection is a foundation for compartmentalisation

Pointer provenance matters!

- CHERI C is a *single-provenance* model
- Every valid pointer is derived from precisely one object (e.g. `malloc()` or stack allocation)
- Pointer arithmetic moves the offset
- Bounds are never implicitly changed

Provenance-carrying integers

`intptr_t` (`__intcap_t`) carries provenance

```
int *cap = ...;
```

No representation change

```
intptr_t iptr = (intptr_t)cap;
```

Safe round trip

```
cap = (int *)iptr;
```

Gets offset

```
long offset = iptr;
```

Non-provenance-carrying integers

Other integer types do not carry provenance

```
int *cap = ...;
```

Gets virtual address

```
long iptr = (long)cap;
```

Invalid pointer
Traps on dereference

```
cap = (int *)iptr;
```

Value stored in offset

```
intptr_t addr = iptr;
```

Memory-safe variadics

- **`va_list`** is a capability
- Caller passes the on-stack arguments in register
- Callee increments offset for next argument

```
// Ooops: Stack corruption
scanf("%ld %ld", &someDouble);
```

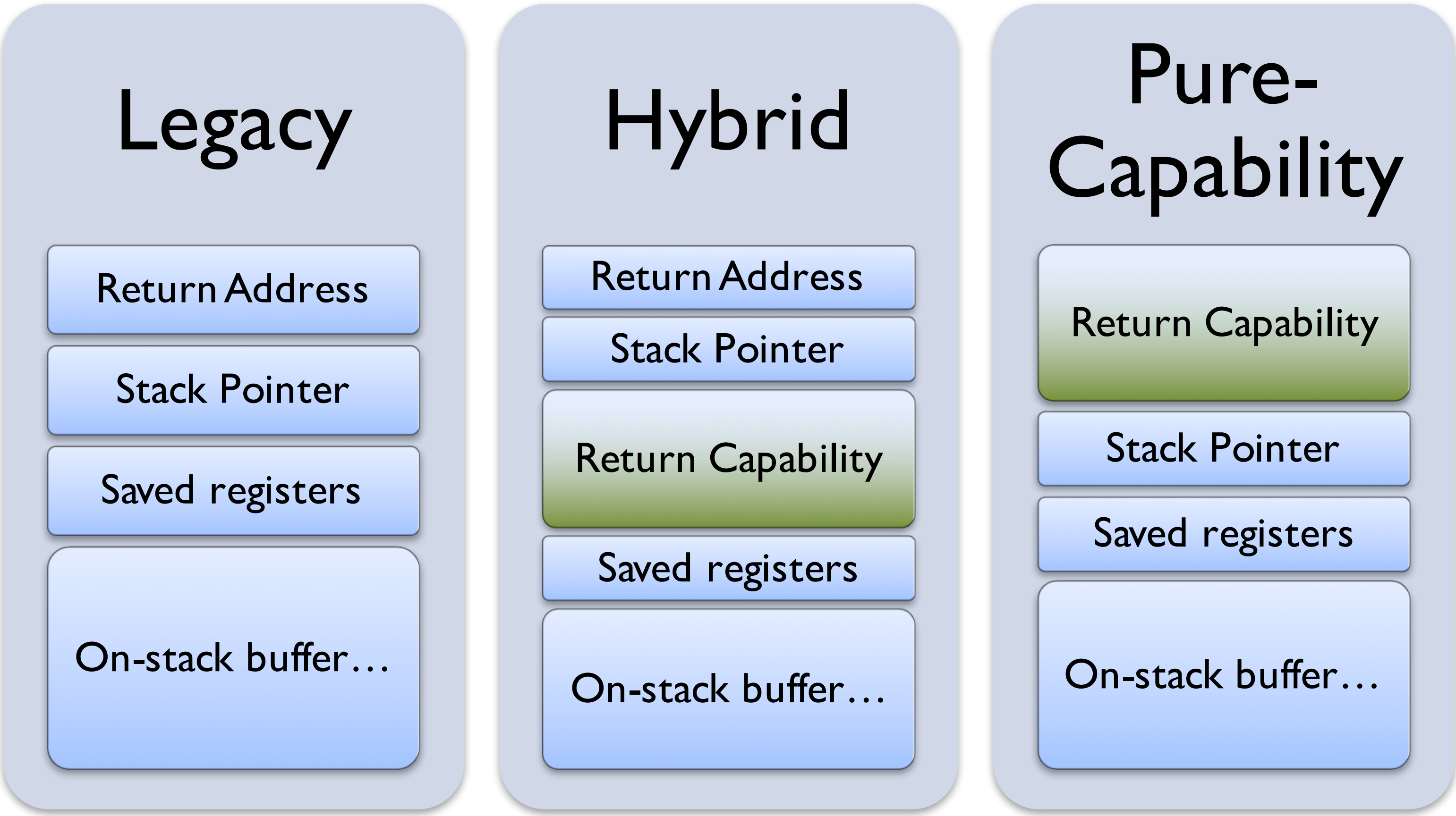
```
// Deep in scanf:
va_list ap;
// Length violation with CHERI:
long x = va_arg(ap, long);
```

Stack Protection

```
sd $ra, $sp
```

```
cgetpccsetoffset  $c17, $ra
csc          $c17, $sp($c11)
```

```
csc  $c17, $sp($c11)
```




```
ld   $ra, $sp
jr   $ra
```

```
clc  $c17, $sp($c11)
cjr  $c17
```

```
clc   $c17, $sp($c11)
cjr   $c17
```

C-like languages

- C++
  - Adds vtables to C structs
  - Multiple inheritance
- Objective-C
  - Adds Smalltalk-like object model, closures

Object pointers should be capabilities

C++ Code-Reuse Attack

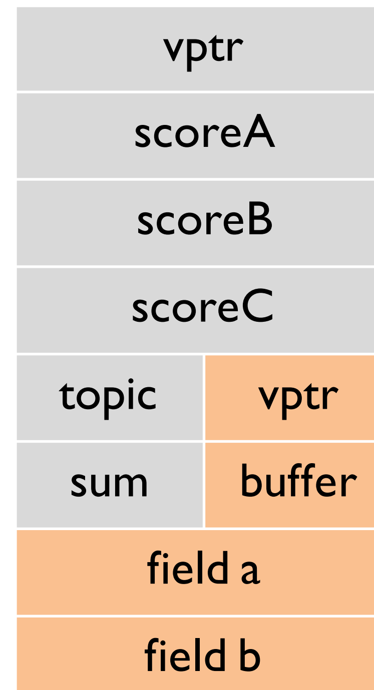
- Example initial gadget:

```
virtual ~Course() {
    for (size_t i = 0; i < nStudents; i++)
    students[i]->decCourseCount();
    delete students;
}
```

- Overlapping objects for dataflow

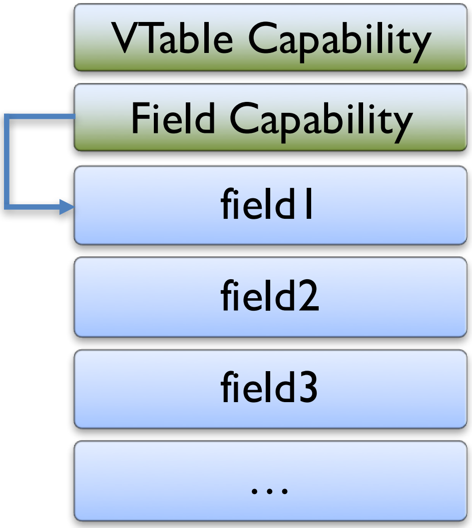
```
virtual calculateSum() {
    sum = scoreA + scoreB + scoreC;
}
```

The computed **sum** field becomes the **buffer** pointer for the next gadget



Possible approach

- Capabilities for vtable pointers, ensuring they always point to the start of a valid vtable
- Capabilities for object integrity
  - Read-only access to vptr
  - Write access only to member fields
- Have to consider CHERI-aware adversary



BACKUP SLIDES

Pure-capability Objective-C

- GNUstep Objective-C runtime
  - Used by WinObjC, CrystalX Android SDK, etc.
  - Complete modern Objective-C implementation
  - 11,533 lines of code, including 839 of assembly
- 8 lines of `intptr_t` changes
- 10 lines of changes for a bitfield encoded in a pointer-sized value
- 163 lines of assembly for CHERI message send function (183 for MIPS, 114 for ARM, 79 for AArch64)

Incremental adoption

- Annotated pointers are capabilities
- Unannotated pointers are integers
- Compiler may use capabilities for non-ABI addresses (e.g., return address)
- Can protect high-value code
- Mostly useful for legacy interfaces to fully memory-safe libraries

Pointer annotation

```
int foo[32];
__capability int *bar = (__capability int*)foo;
```

- Only specially annotated pointers are capabilities
- Compiler attempts to infer bounds

```c
int foo(char *);
int bar(void) {
	char buffer[128];
	return foo(buffer);
}
```

Function Prolog

MIPS

```
bar:
 daddiu   $sp, $sp, -160
 sd   $ra, 152($sp)
 sd   $fp, 144($sp)
 sd   $gp, 136($sp)
 move       $fp, $sp
```

CHERI

```
bar:
 daddiu   $sp, $sp, -192
 csd $fp, $sp, 184($c11)
 csd $gp, $sp, 176($c11)
 csc $c17, $sp, 128($c11)
 move       $fp, $sp
```

Save return address

```c
int foo(char *);
int bar(void) {
	char buffer[128];
	return foo(buffer);
}
```

GOT address setup

MIPS

```
lui $1,
      %hi(%neg(%gp_rel(bar)))
daddu   $1, $1, $25
daddiu  $gp, $1,
      %lo(%neg(%gp_rel(bar)))
```

CHERI

```
cgetoffset  $25, $c12
lui $1,
   %hi(%neg(%gp_rel(bar)))
daddu   $1, $1, $25
daddiu  $gp, $1,
%lo(%neg(%gp_rel(bar)))
```

Get PCC-relative offset of function
(Will be obsoleted by a CHERI linker)

```c
int foo(char *);
int bar(void) {
	char buffer[128];
	return foo(buffer);
}
```

Set base and bounds for buffer

MIPS

```
daddiu  $4, $fp, 8
```

CHERI

```
daddiu     $1, $fp, 0
csetoffset $c1, $c11, $1
daddiu     $1, $zero, 128
csetbounds $c3, $c1, $1
```

Hope that foo doesn't overflow the buffer!

```c
int foo(char *);
int bar(void) {
        char buffer[128];
        return foo(buffer);
}
```

Get address of `foo`

MIPS

```
ld  $25, %call16(foo)($gp)
```

CHERI

```
daddiu  $1, $gp, %call16(foo)
cfromptr $c1, $c0, $1
cld      $1, $zero, 0($c1)
cgetpccsetoffset   $c12, $1
```

Longer sequence on CHERI because we use MIPS relocations with CHERI instructions
(Will be fixed with a CHERI linker)

```c
int foo(char *);
int bar(void) {
	char buffer[128];
	return foo(buffer);
}
```

Call foo

MIPS	CHERI
`jalr $25, $ra`	`cjalr $c17, $c12`

```
int foo(char *);
int bar(void) {
	char buffer[128];
	return foo(buffer);
}
```

Function Epilog

MIPS

```
move      $sp, $fp
   ld   $gp, 136($sp)
   ld   $fp, 144($sp)
   ld   $ra, 152($sp)
   jr   $ra
   daddiu   $sp, $sp, 160
```

CHERI

```
move      $sp, $fp
clc $c17, $sp, 128($c11)
cld $gp, $sp, 176($c11)
cld $fp, $sp, 184($c11)
cjr $c17
daddiu   $sp, $sp, 192
```

Reload return address