CheriABI

Hardware enforced memory safety for FreeBSD

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Punchline: it really does work

- Full FreeBSD operating system with spatial and referential memory safety
  - Covers programs, libraries, and linkers
  - Kernel access to user memory
- Performance is generally acceptable
- Significant 3rd-party software works: PostgreSQL database, Webkit

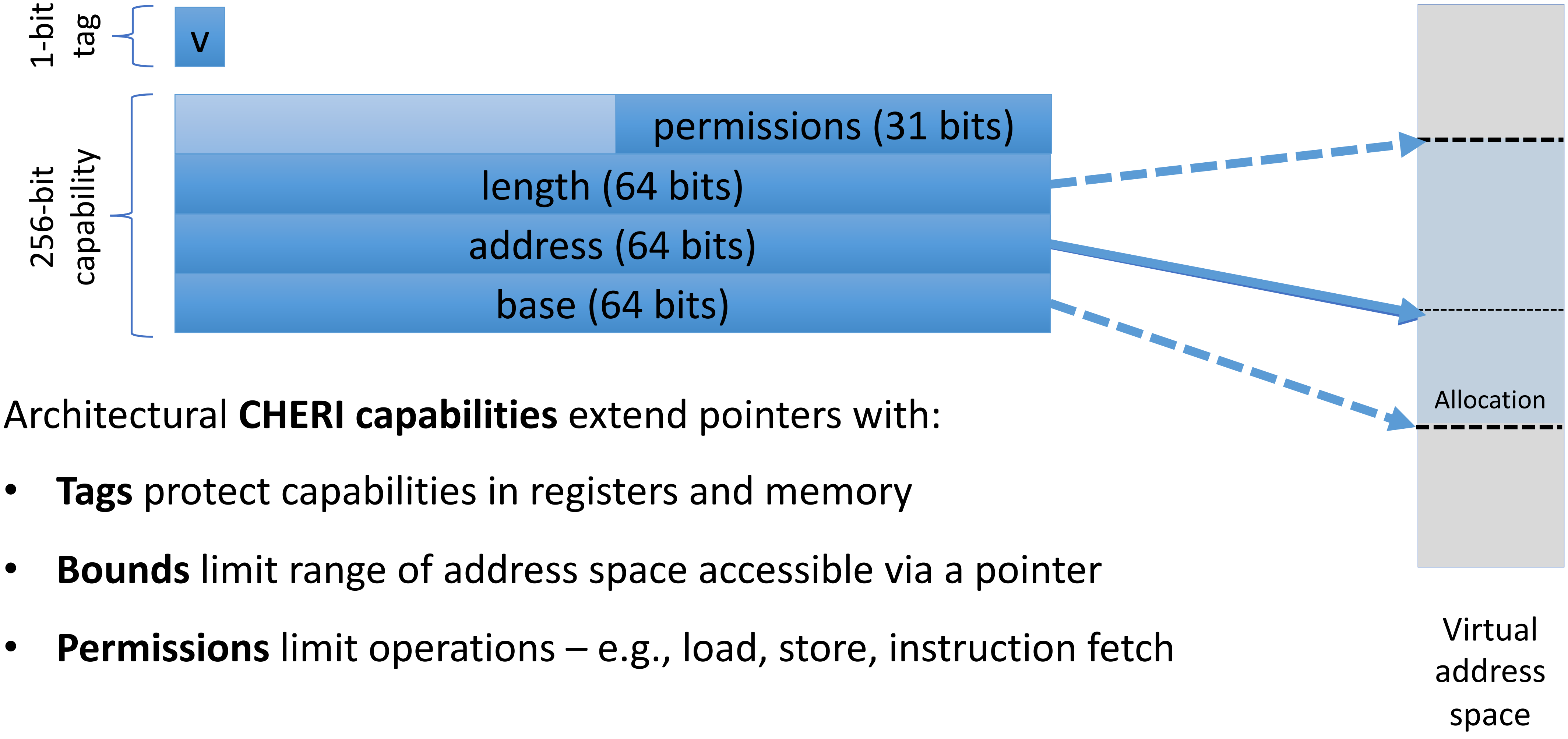
Introduction to CHERI

- CHERI introduces a new register type: the **capability**
  - In addition to integer and floating point
- CHERI capabilities grant access to bounded regions of virtual address space
  - Protected by tags

Watson, et al. **CHERI: a research platform deconflating hardware virtualization and protection.** RESoLVE 2012.

Woodruff, et al. **The CHERI capability model: Revisiting RISC in an age of risk**. ISCA 2014.

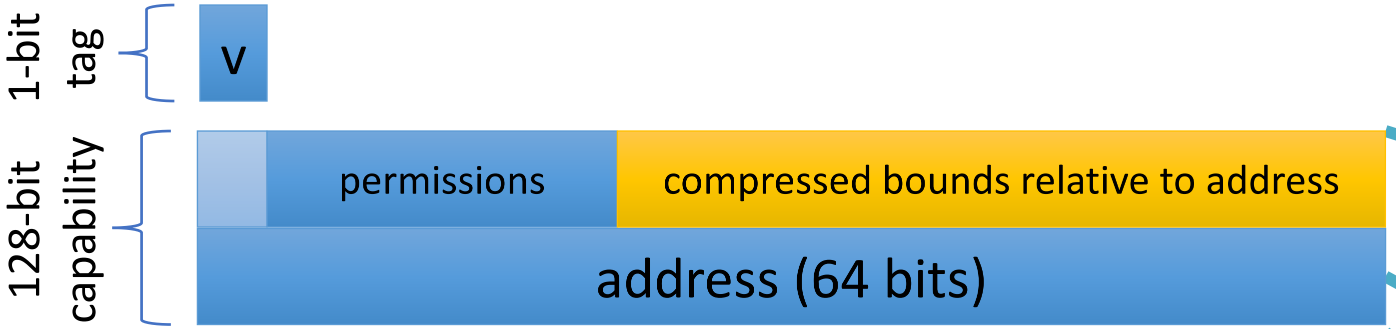
Architectural CHERI capabilities

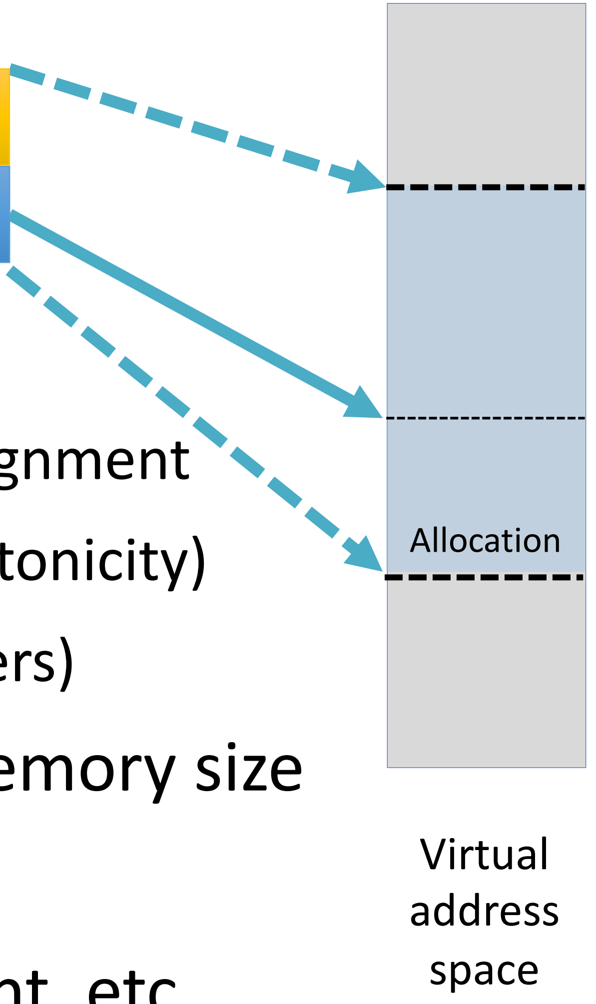


Architectural **CHERI capabilities** extend pointers with:

- **Tags** protect capabilities in registers and memory
- **Bounds** limit range of address space accessible via a pointer
- **Permissions** limit operations – e.g., load, store, instruction fetch

128-bit compressed capabilities





- **Compress bounds** relative to 64-bit virtual address
  - Floating-point bounds mechanism constrains bounds alignment
  - Security properties maintained (e.g., provenance, monotonicity)
  - Strong C-language support (e.g., for out-of-bound pointers)
- DRAM tag density from 0.4% to 0.8% of physical memory size
- Full prototype with full software stack on FPGA
- Implications for memory allocators, object alignment, etc

CHERI memory operation

- All memory access via CHERI capabilities
  - Explicit (new instructions):
    - Capability load, store, branch, jump
  - Implicit (legacy MIPS ISA):
    - via Default Data Capability (DDC) or Program Counter Capability (PCC)

CHERI capability manipulation

- Capabilities are used and manipulated in capability registers with capability instructions
  - Manipulations are monotonic (can only reduce bounds and permissions)
  - `CAndPerm cd, cb, rt`
  - `CSetAddr cd, cs, rs`
- Capabilities can be stored in memory, protected by tags
  - Non-capability stores clear tags

Capabilities as C pointers

- CHERI capabilities are designed for use as C pointers
  - Allowed to be out of bounds between dereferences
  - Can store 64-bit integers (untagged)
  - No protection tables or privileged operations
- Two compilation modes:
  - Hybrid: `__capability` annotation applied to select pointers
  - Pure-capability: all pointers are capabilities

Chisnall, et al. **Beyond the PDP-11: Processor support for a memory-safe C abstract machine.** ASPLOS 2015.

CheriABI: Pure-capability process environment

- Built on CheriBSD (FreeBSD modified for CHERI)
- All program pointers are capabilities
  - Including syscall arguments and return values
- Goal: Bounds are minimized
  - C-language objects
  - Pointers provided by the kernel
- Goal: run pure-capability programs with simple recompilation

Watson, et al. **CHERI: A Hybrid Capability-System Architecture for Scalable Software Compartmentalization.** Oakland 2015.

Chisnall, et al. **CHERI-JNI: Sinking the Java security model into the C.** ASPLOS 2017.

Implementation: kernel

- CheriABI is implemented as a compat layer (i.e. freebsd32)
- The kernel is a hybrid CHERI-C program
  - Pointers to userspace are annotated with `__capability` and are capabilities.
  - Select data structures (e.g. `struct iovec`, signal bits) converted to store capabilities.
- All userspace access via capabilities
  - Capability aware versions of userspace access functions: `copyin_c/copyout_c/fueword_c`, etc
  - Non "_c" verisons return error for CheriABI processes
  - Capabilities not copied to/from userspace by default
    - Special copyincap/copyoutcap used to ensure copy is intentional

Implementation: userspace

- Libraries live in /usr/libcheri
  - Built before programs
- Programs can compile and link as legacy, hybrid, or pure-capability
- Almost-full support for external LLVM toolchain for mips64

Abstract capabilities

How should the systems programmer **think** about bounds?

New concept: *abstract capability*

- Set of permissions of the process
- Tracks ghost state across swapping, etc
- Constructed and maintained by a collaboration of the kernel and language runtime

System startup

Power-on state

Registers

DDC	RWX 0x0 - 0xFF…FF
PCC	RWX 0x0 - 0xFF…FF
C1-31	NULL

Memory

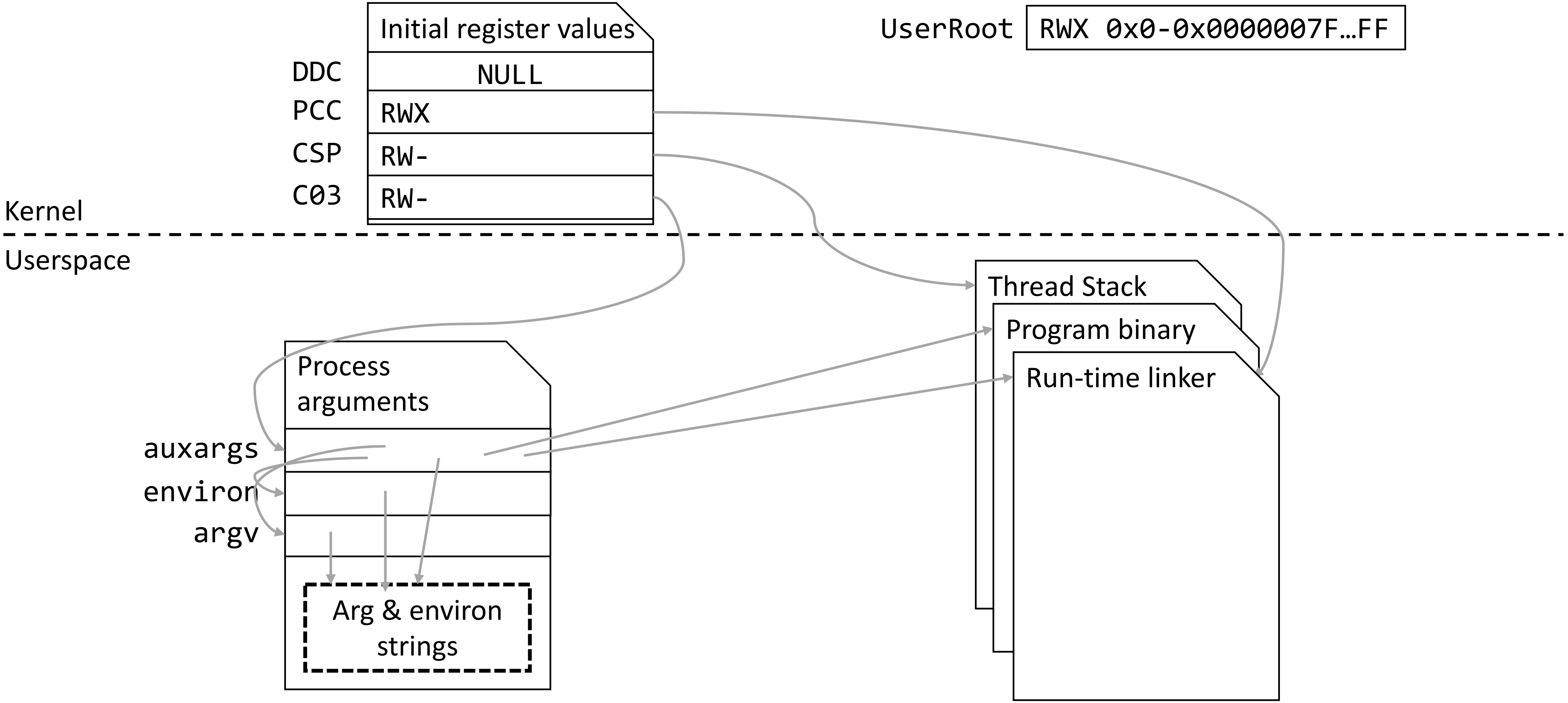
All tags clear

Early boot

DDC	RW- 0x0 - 0xFF…FF
PCC	R-X 0x0 - 0xFF…FF
C1-31	*Working set*

UserRoot	RWX 0x0-0x0000007F…FF
SwapRoot	RWX 0x0 - 0xFF…FF

Execve



Initial register values
DDC
NULL
PCC
RWX
CSP
RW-
C03
RW-
UserRoot
RWX 0x0-0x0000007F…FF
Kernel
Userspace
Thread Stack
Program binary
Run-time linker
Process arguments
auxargs
environ
argv
Arg & environ strings

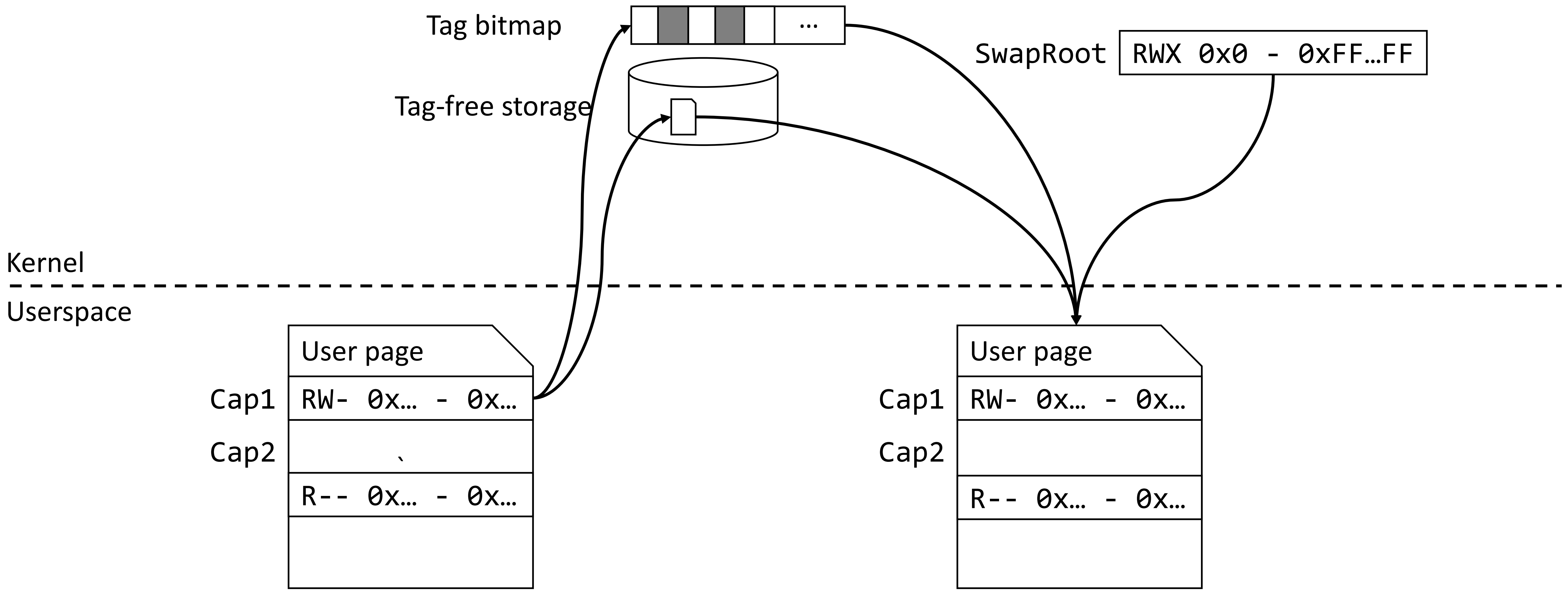
Virtual-memory system

- Programmer visible:
  - Provides capabilities to newly mapped regions via `mmap()` and `shmat()`
  - Alters and frees mappings
- Abstract capability maintenance:
  - Ensures correct virtual to physical mappings
  - Preserves stored capabilities in swapped pages

Virtual-memory system: mmap

- mmap() allocates virtual address space and changes mappings
- In CheriABI returns a bounded pointer
  - Imprecise mapping requests rejected
  - User must round-up unpresentable requests
- Permissions are set based on page permissions
  - PROT_MAX() extension allows PROT_NONE mappings for reservation

Virtual-memory system: swap



Run-time linker

- Loads and links dynamic libraries
- Resolves symbols and synthesizes capabilities
- Jumps to program entry point

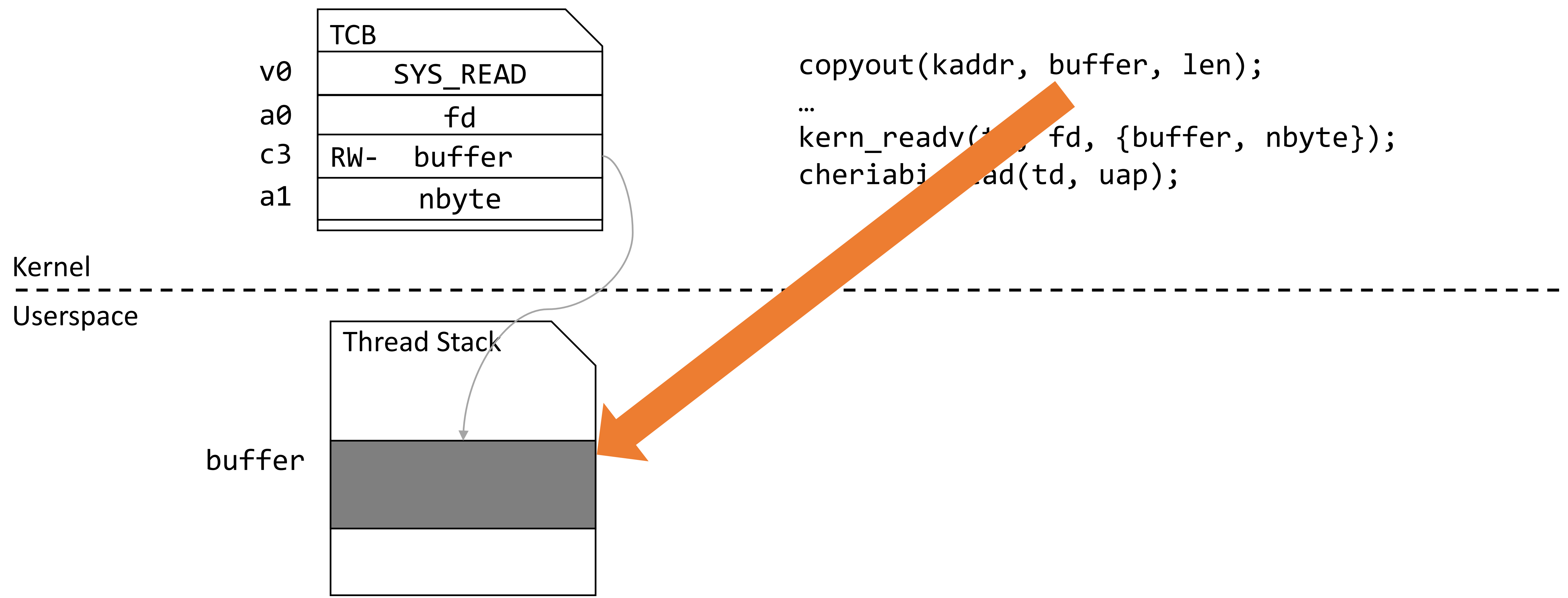
- Provides on-demand loading of libraries and supports exception handling

C runtime

- Objects allocated by `malloc()` are bounded to requested size
- `realloc()` adjusts bounds or allocates new storage
- Thread-local storage is bounded
  - Currently to per-thread storage
- Compiler generated code sets bounds on stack, automatic, and global objects as required

System calls

```
read(fd, buffer, nbyte);
```



Kernel code changes: read()

```
int user_read(struct thread *td, int fd, void * __capability buf,
    size_t nbyte)
{
        struct uio auio;
        kiovec_t aiov;
        if (nbyte > IOSIZE_MAX)
                return (EINVAL);
        IOVEC_INIT_C(&aiov, buf, nbyte);
        auio.uio_iov = &aiov;
        …
        return (kern_readv(td, fd, &auio));
}
```

Called by sys_read() and cheriabi_read()

New init macro for struct iovec

Required changes: pointer alignment

```
 label_done:
         if (metadata_thp_madvise()) {
                 /* Set NOHUGEPAGE after unmap to avoid kernel defrag
                    . */
-                assert(((uintptr_t)addr & HUGEPAGE_MASK) == 0 &&
+                assert(__builtin_is_aligned(addr, HUGEPAGE) &&
                     (size & HUGEPAGE_MASK) == 0);
                 pages_nohuge(addr, size);
         }
```

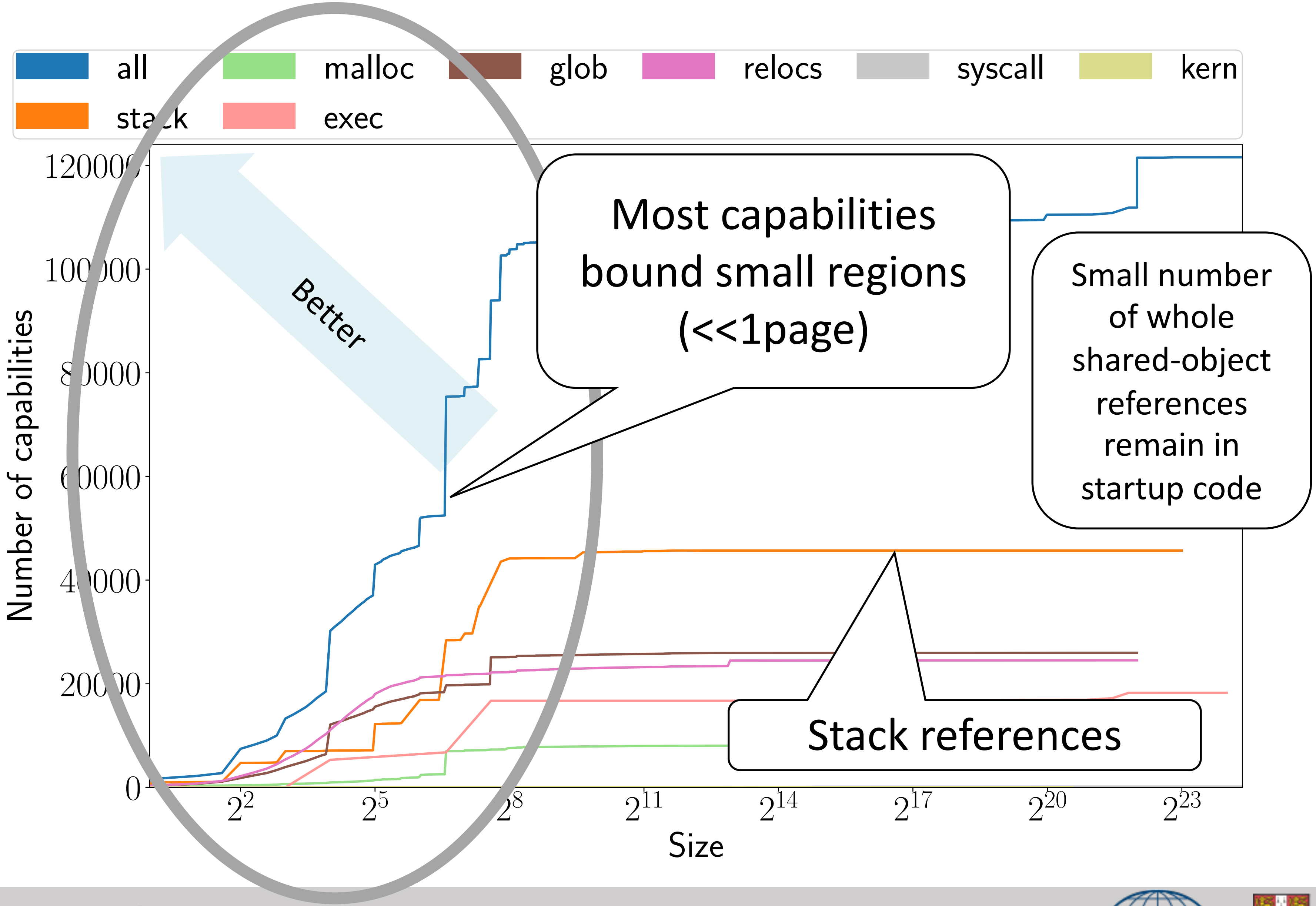
Required changes: pointer provenance

```
        if ((nstrings = realloc(we->we_strings, we->we_nbytes)) ==
            NULL) {
                error = WRDE_NOSPACE;
                goto cleanup;
        }
        for (i = 0; i < vofs; i++)
-               if (we->we_wordv[i] != NULL)
-                       we->we_wordv[i] += nstrings - we->we_strings
    ;
+               if (we->we_wordv[i] != NULL) {
+                       we->we_wordv[i] = nstrings +
+                           (we->we_wordv[i] - we->we_strings);
+               }
        we->we_strings = nstrings;
```

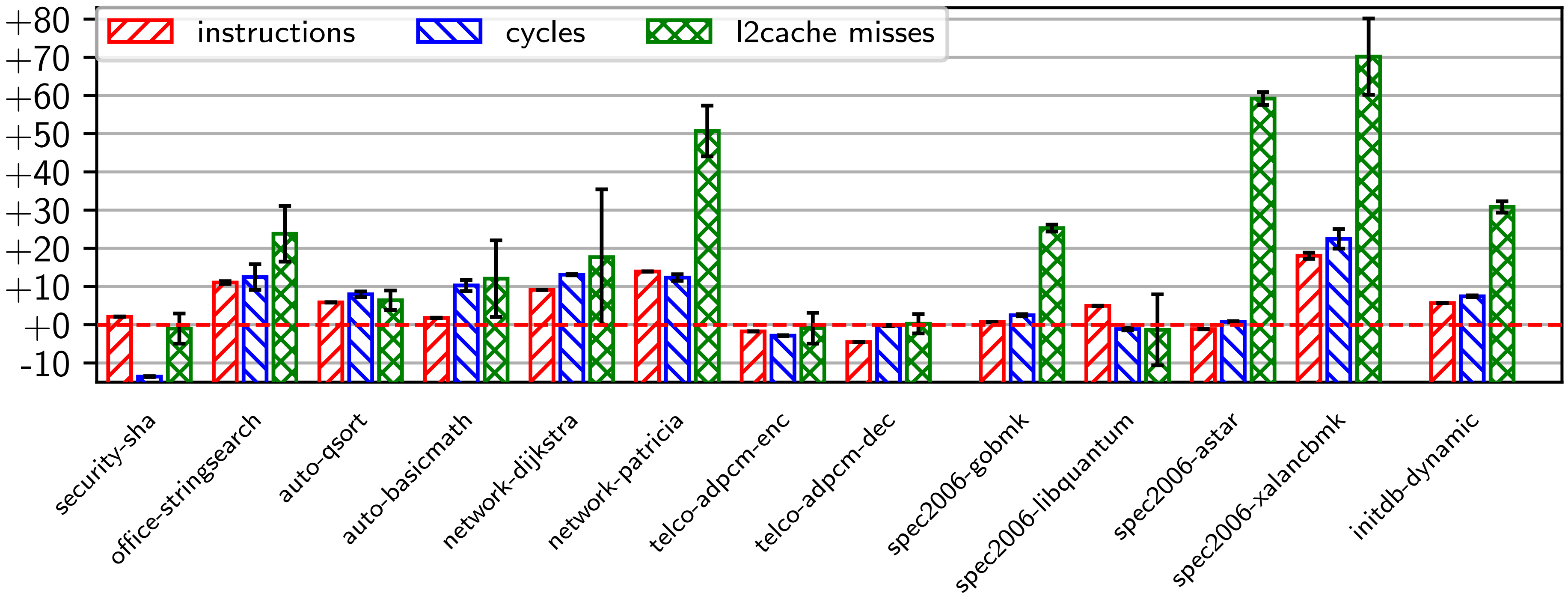
Required changes: summary

- Userspace: 1% (~200) of files required changes
  - Concentrated in libraries
  - Most programs require no changes
- Kernel: <6% of files (~750) required changes
  - Pervasive changes to `iovec`, signal handlers, network interface `ioctl` handlers
  - A pure-capability kernel could reduce changes
- Many changes improve code quality
  - We have upstreamed many to FreeBSD (compat32 improvements, etc)

Capability bounds minimization (OpenSSL)



Performance



- Micro-benchmark performance generally acceptable
  - <10% overhead in most cases
  - Graph excludes crypto and bit-manipulation outliers

Reflections on using FreeBSD for CheriABI

- Good:
  - Well-abstracted process ABI infrastructure
    - SysV stack ABI somewhat baked in
  - Central, generated system call tables, stubs, etc
  - Single, hackable build system
- Bad
  - Centralized `copyin`/`copyout` for `ioctl` divorces copy from types
  - Tests require ports/packages (kyua)
    - No easy way to build kyua static

Work in progress

- Porting ISA from MIPS64 to RISC-V
- New compressed capability format
- Temporal memory safety
- Make CheriABI the default ABI
  - Add a compat/freebsd64
- Pure-capability kernel

Future work on FreeBSD

- More compatX cleanup
  - Code deduplication
  - Remove separate syscalls.master
- Rework ioctl interface
  - Konrad Witaszczyk (def@) is working in this area
- Refactor use of initial stack for arguments
  - Needed for CheriABI, likely helpful for ASLR
- Upstream CHERI/CheriABI support
  - Hardware platform required, but hopefully coming

Conclusions

- Full UNIX-like operating system with spatial and referential memory safety
  - Covers programs, libraries, and linkers
  - Kernel access to user memory
- Some fundamental operating system changes required
  - Generally non-disruptive
- 3rd-party software works: PostgreSQL database, Webkit

Further Reading

http://cheri-cpu.org/

Watson, et al., **Capability Hardware Enhanced RISC Instructions: CHERI Instruction-Set Architecture (Version 7),** Technical Report UCAM-CL-TR-927, Computer Laboratory, Cambridge UK, October 2018.

Davis, et al., **CheriABI: Enforcing Valid Pointer Provenance and Minimizing Pointer Privilege in the POSIX C Run-time Environment (Extended Version),** Technical Report UCAM-CL-TR-932, Computer Laboratory, Cambridge UK, January 2019.

Woodruff, et al., **CHERI Concentrate: Practical Compressed Capabilities,** IEEE Transactions on Computers, (forthcoming).

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