CTSRD

CRASH-worthy Trustworthy Systems Research and Development

CheriABI

A pure-capability OS process environment

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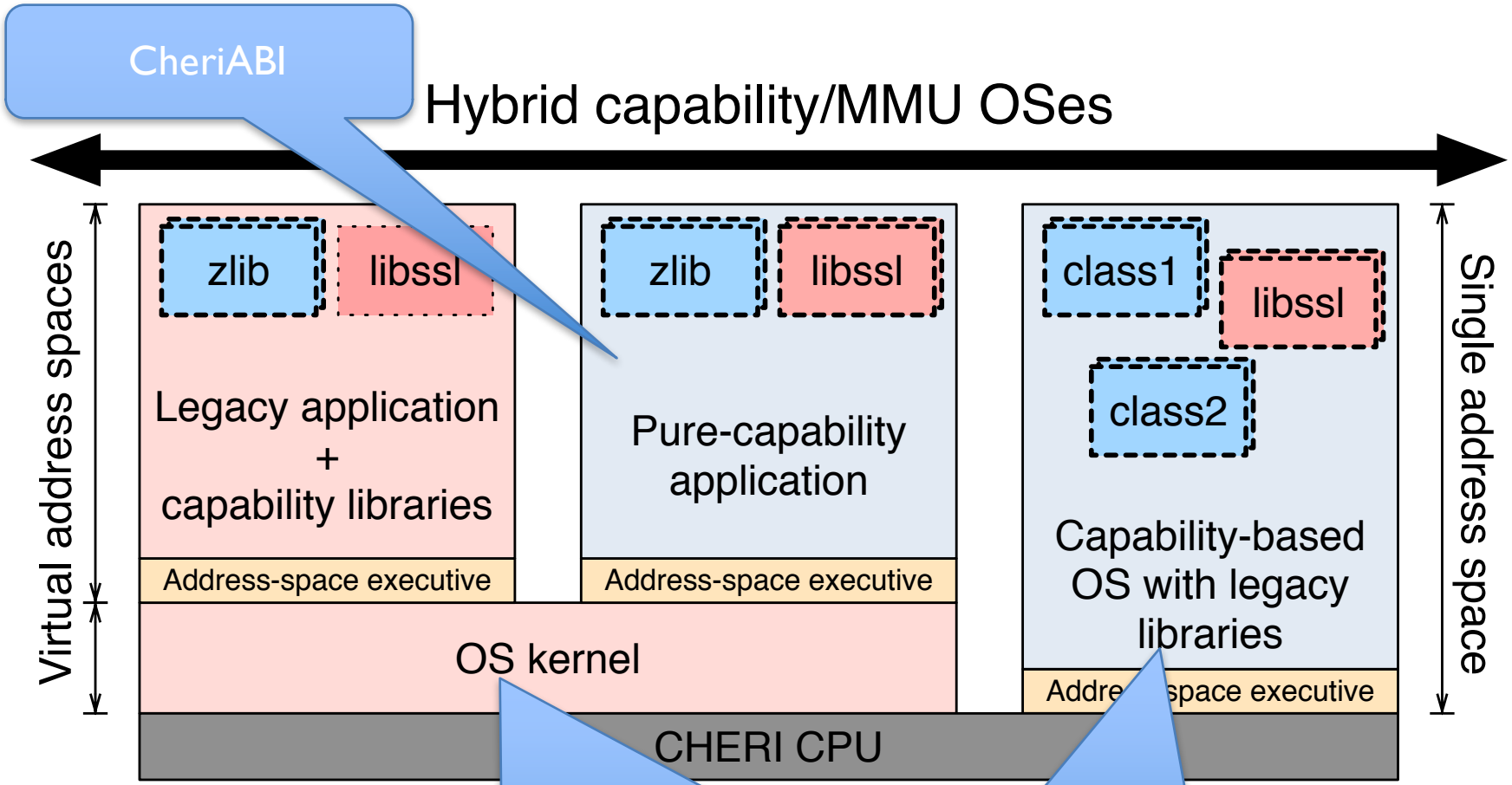
Software deployment models



Hybrid MMU-capability models: protection and compartmentalization within virtual address spaces

Single-address-space systems are possible but not yet our focus

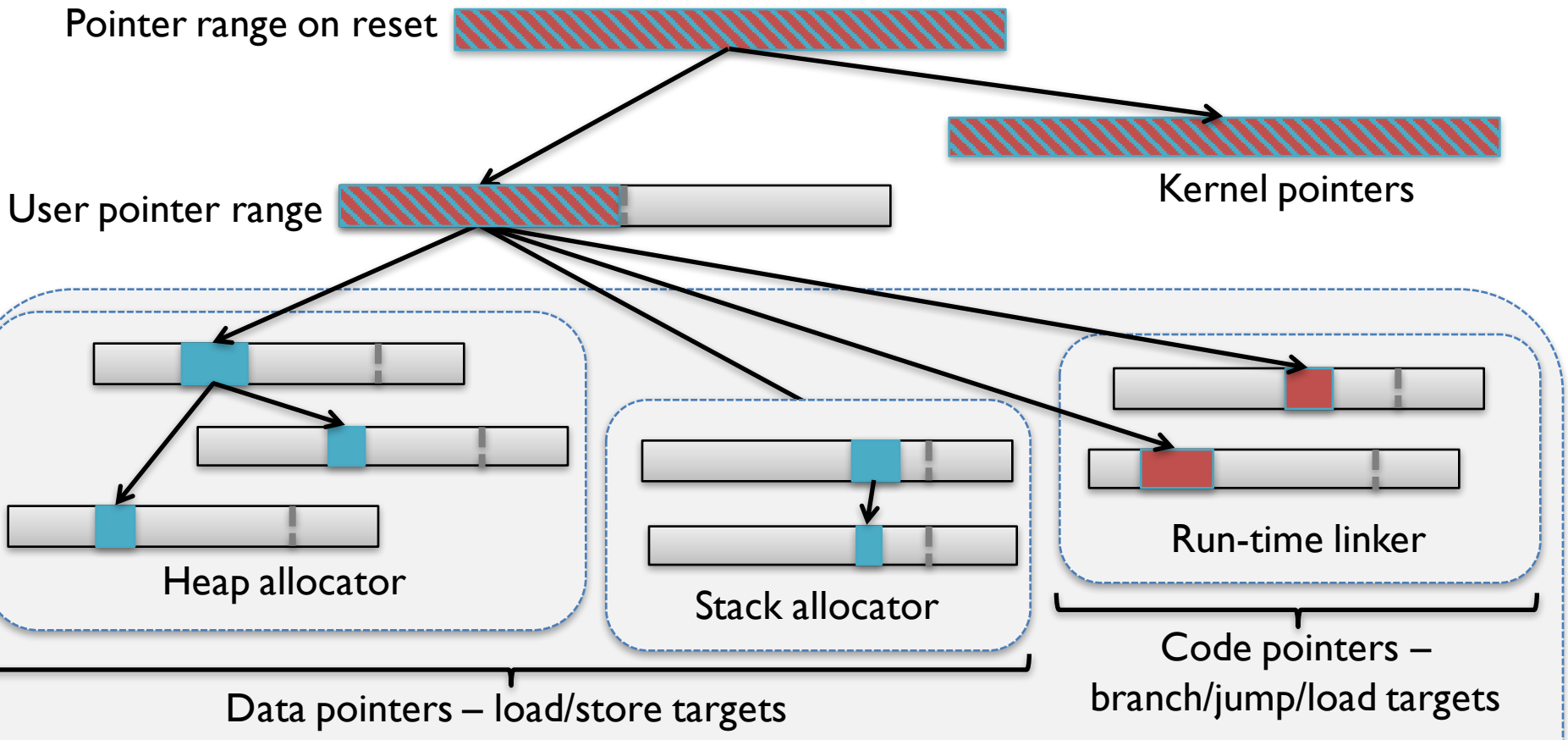
Aim of CheriABI: pure-capability POSIX applications

- **Goals:**
  - Recompile to get memory safety and CFI
  - Explore pure-capability process environment
- **Principles:**
  - Change implementation, not declarations
  - Pointers to C objects are *data* capabilities
    - malloc() allocates data references, never code
  - Page table manipulation syscalls allow (controlled) escape from C memory model

CheriABI challenges

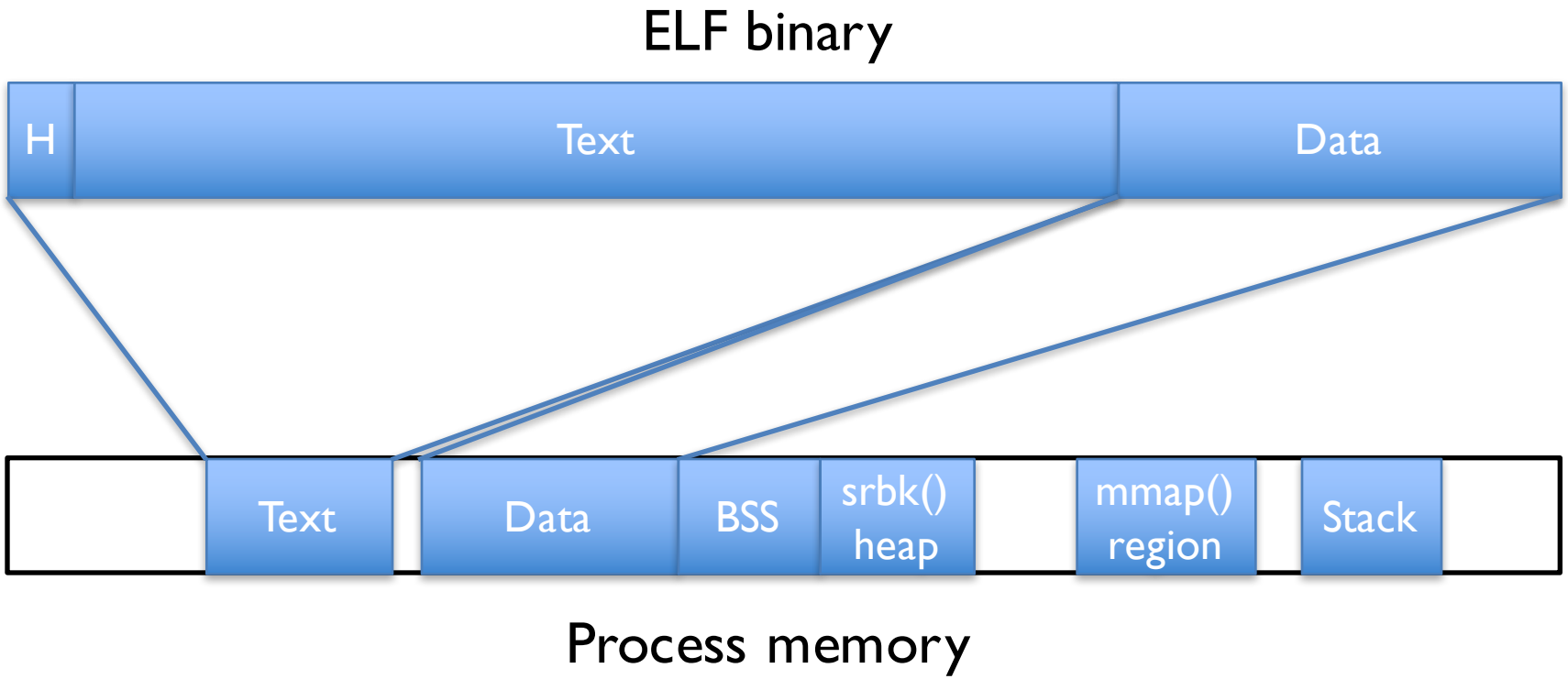
- Managing sources of capabilities
  - Kernel/run-time linker file mappings, argv, environ
  - Language level: malloc(), stack, globals, TLS
  - Page-table mappings
    - POSIX APIs allow any page to be replaced!
- Translating capabilities and capability containing objects into capability-oblivious kernel
  - Validating translations
- Composing defacto-POSIX with memory safety

Enforcing pointer provenance, bounds, permissions, and monotonicity

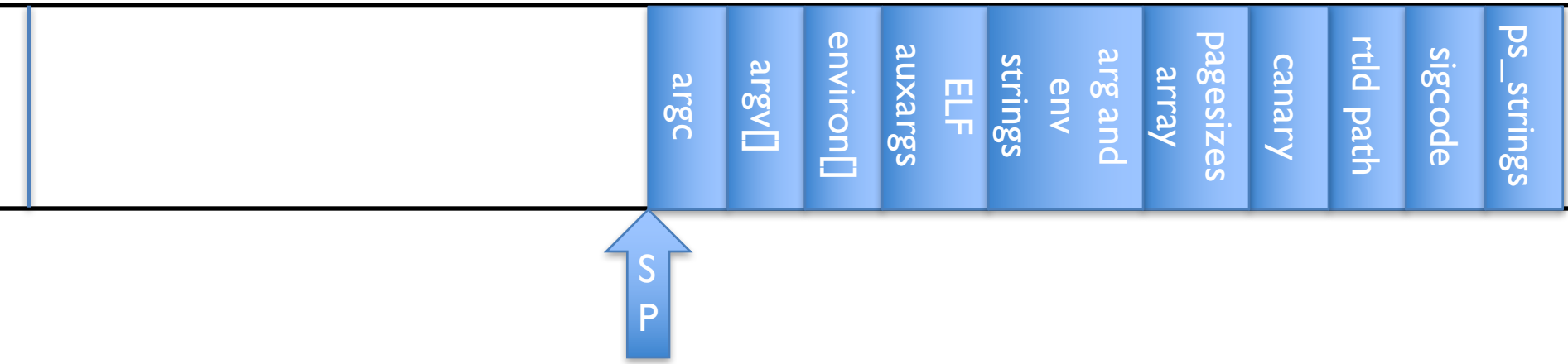


Valid userspace pointer set – pointers not generated using derivation rules are not part of the valid provenance tree and should not be dereferenceable

MIPS process layout



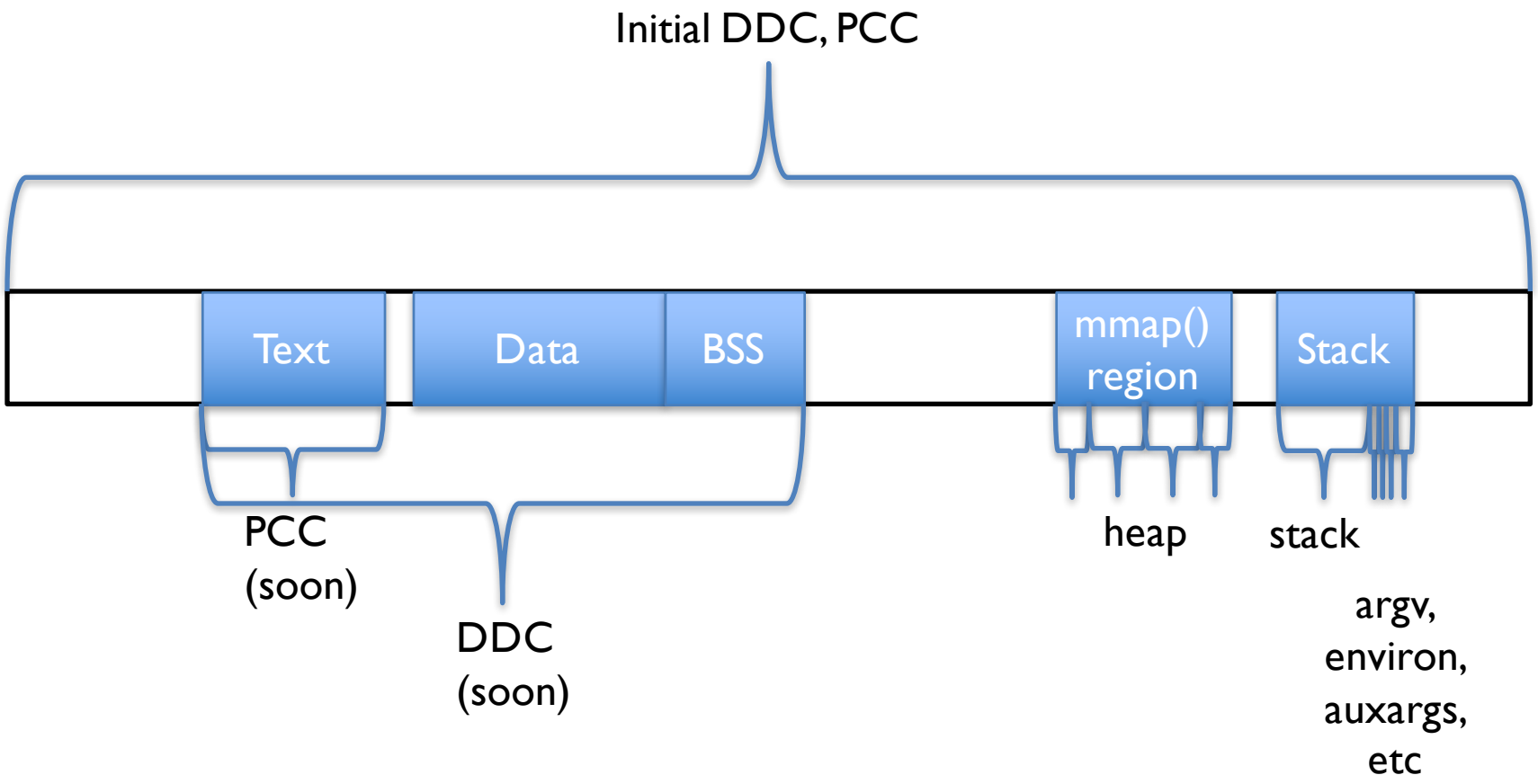
SCO i386 ABI stack



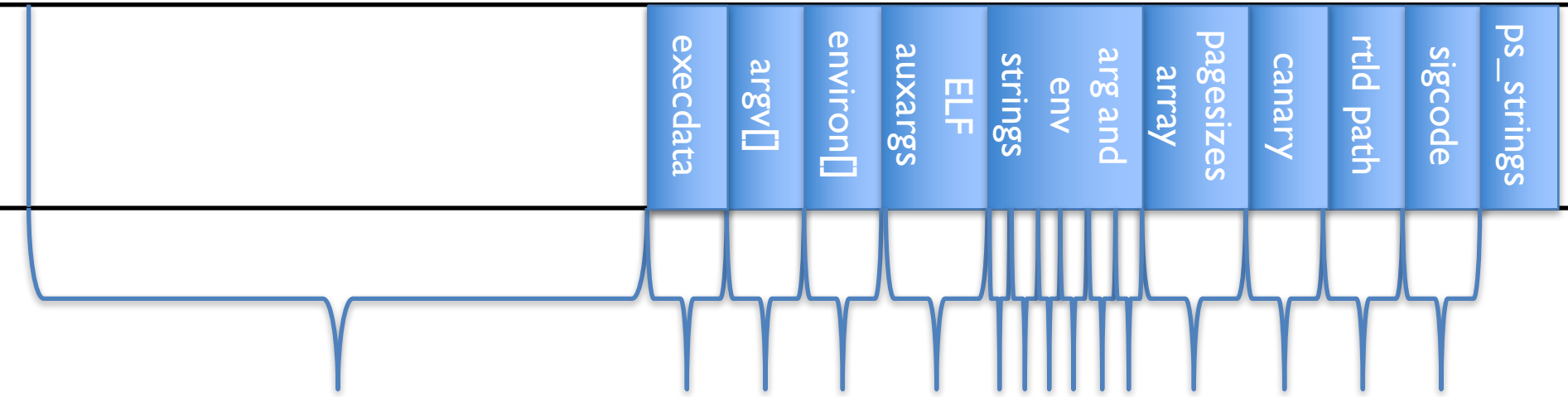

```
_start(char **ap, …) {
    …
      argc = * (long *) ap;
      argv = ap + 1;
      env  = ap + 2 + argc;
    …
```

```
_init_tls() {
    …
    sp = (Elf_Addr *) environ;
    while (*sp++ != 0)
        ;
    aux = (Elf_Auxinfo *) sp;
```

CheriABI process layout



CheriABI stack



- Stack capability excludes strings, etc
- Remove ps_strings
- Capabilities for each object
- argc replaced with cheriabi_execdata
- Capability to execdata passed to _start as argument

```
struct cheriabi_execdata {
        size_t      ce_len;
        int         ce_argc;
        char        **ce_argv;
        char        **ce_envp;
        struct cheriabi_auxarg *ce_auxargs;
        struct ps_strings *ce_ps_strings;
};
```

mmap() in CheriABI

- The mmap() syscall allocates address space
  - Is a direct and indirect source of capabilities
- mmap() also replaces mappings
  - Changes the contents of capabilities
    - Takes capability argument covering page(s)
    - Will require capability permission bit
  - May upgrade permissions on capabilities!

mmap() alignment

- Compressed capabilities require alignment constraints to ensure representability
- New alignment constraints
  - MAP_ALIGNED_CHERI
  - MAP_ALIGNED_CHERI_SEAL
- Flags constrain alignment and assert that the length is representable
  - Usable in CheriABI and native code
- MAP_CHERI_NOSETBOUNDS allows unrepresentable subregions to be mapped within reservation

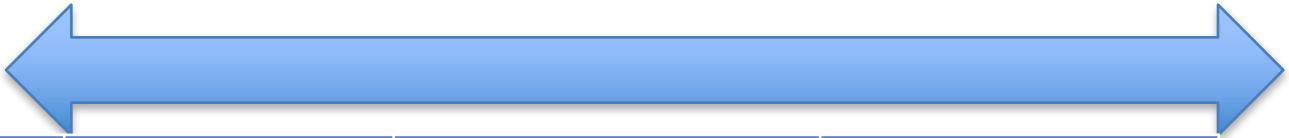
mmap() continued

- Pattern of PROT_NONE reservation followed by mapping sub regions requires two changes:
  - Reservation must have desired permissions for capability followed by mprotect() to remove permissions
  - Use the MAP_CHERI_NOSETBOUNDS flag to avoid potentially unrepresentable sub-regions
- New APIs required

CheriABI syscall translation challenges

- Pointers and integers differ in registers
  - Different registers on MIPS
  - Similar issues with converged register files
- Pointers may point to structures containing pointers – similar to 32-bit/64-bit compat
  - Translation required
- Variadic system calls (fcntl, ioctl, open, etc)
- Multiplexed system calls (ioctl, _umtx)

System-call argument translation spectrum



	Pointer Translation	Capability validation	Capabilities in kernel
Kernel acts via	Virtual address	Virtual address	Capability
Kernel implements user memory model	-	tag, length*, perms	all
Issues	Capabilities bypassed	Annotations must be correct. Subject to confused deputy attacks.*	Need to translate arguments from non-capability ABIs.

* No length on strings or length not bound at time of check

Syscall argument translation vs validation

Translation

```
tag = cheri_gettag(argcap);
if (tag)
        ptr = cheri_ctoprt(argcap, kdc);
else
        ptr = cheri_getbase(argcap) +
            cheri_getoffset(argcap);
```

Validation

```
if (!cheri_gettag(argcap))
        return (EPROT);
if (cheri_getsealed(argcap))
        return (EPROT);
if (cheri_getperms(argcap) &
    reqperms) != reqperms)
        return (EPROT);
if (cheri_getlen(argcap) –
    cheri_getoffset(argcap)  < reqlen)
        return (EPROT);
ptr = cheri_ctoptr(argcap, kdc);
```

Syscall annotations drive validation

```
int open(_In_z_ char *path, int flags, int mode);

int cheriabi_readv(int fd, _Inout_updates_(iovcnt)
    struct iovec_c *iovp, u_int iovcnt);

int minherit(_Pagerange_(len) void *addr,
    size_t len, int inherit);

int accept(int s,
    _Out_writes_bytes_(*anamelen)
    struct sockaddr *name,
    _Inout_opt_ socklen_t *anamelen);
```

CheriABI results

- CheriBSD tests run and largely pass
- Variety of applications work without modification
  - From echo to ssh
  - Spatial memory safety for "free"
- Progressing toward multi threaded, dynamically linked applications
  - Using modern, thread-aware malloc()
  - Starting work on runtime linker

CheriABI conclusions

- CheriABI runs (mostly) unmodified POSIX applications with memory safety and CFI
- We are exploring transition paths:
  - From a monolithic, capability-oblivious kernel to a capability-aware kernel.
  - From traditional C to memory-safe C programming environment

BACKUP SLIDES

Kernel Changes

Component	File	Lines +	Lines -
Headers	19	1424	11
CHERI initialization	2	49	4
Context management	2	392	10
Exception handling	3	574	90
Memory copying	2	122	0
Virtual memory	5	398	27
Object capabilities	2	883	0
System calls	2	76	0
CheriABI	6	2855	0
Signal delivery	3	327	71
Process monitoring/debugging	3	298	0
Kernel debugger	2	264	0