Advanced Operating Systems (and System Security)
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Cross ring data move

1. Segmentation based protection breaks
2. Kernel level actual data move facilities
3. Enhanced hardware/software data move support

User/kernel interactions so far

- We can change execution flow between user and kernel
- The effects are
  - ✓ the switch of segmentation information (CS, DS ….)
  - ✓ the switch of the CPL
- We can use CPU general purpose registers to
  - ✓ Post <u>register-fitting input data</u> to the kernel
  - ✓ Get <u>register-fitting results</u> from the kernel
- What about the need for exchanging larger data sets?
  - ✓ see, e.g., Posix `read()/write()`, or Win-API `ReadFile()/WriteFile()`

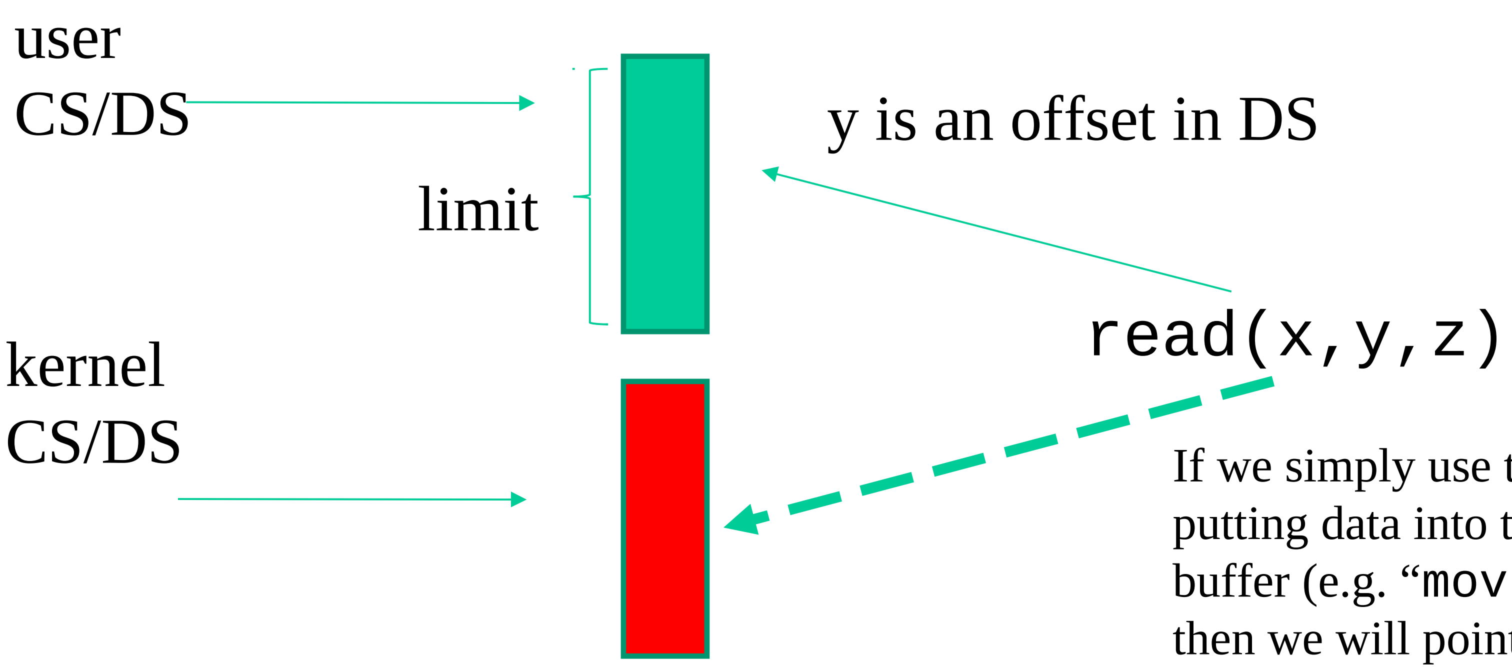
Usage of pointers

- Clearly, to exchange larger data sets between user and kernel software we use buffers, hence pointers
- Pointers fully break the ring-based protection model
  - ✓ A pointer value can be defined at user level
  - ✓ The actual pointed content can be (over)written or read executing at kernel level
  - ✓ Without additional mechanisms, kernel software can be tampered
- The actual solution to this problem depends on a lot of factors
  - ✓ Actual segmentation support in the hardware
  - ✓ Absence or presence of additional protection mechanisms in the hardware

The case of flexible segmentation

- This is x86 protected mode segmentation
- We can make, e.g., CS and DS point to whatever we want in the linear address space
- Actual advantages and problems:
  - ✓ Segment full separation in the address space will allow protecting illegal read/writes from kernel segments
  - ✓ We need a mechanism for making this protection occur seamless to the software development process

A scheme



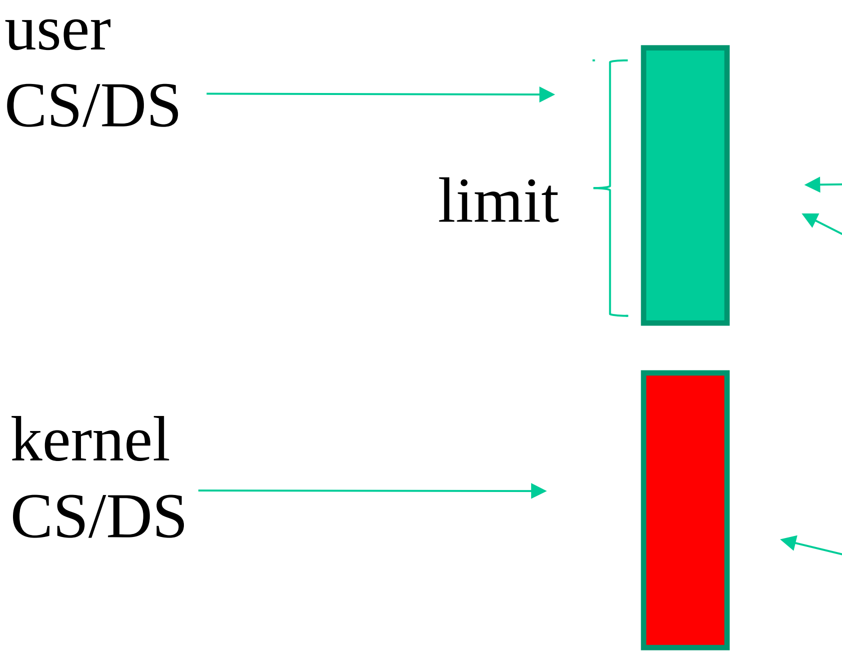
If we simply use the offset y for putting data into the destination buffer (e.g. “`mov source,(y)`”) then we will point to kernel level DS upon kernel access

If we use pure compiler-selected segmentation then the ring model is broken

A solution

- Pieces of kernel code for moving data cross user/kernel must be "handcrafted" (since choices involving segments must be carefully handled – not solely based on compilers)
- We can use a programmable segment selector (e.g. FS) to do this
  - ✓ map FS to the user DS
  - ✓ move data using the pointer 'y' applying the displacement to FS
- These operations are generally called 'segmentation fixup'
- Clearly they have a cost in terms of processor state setup for carrying out the memory copy

Solution details



y is an offset in DS

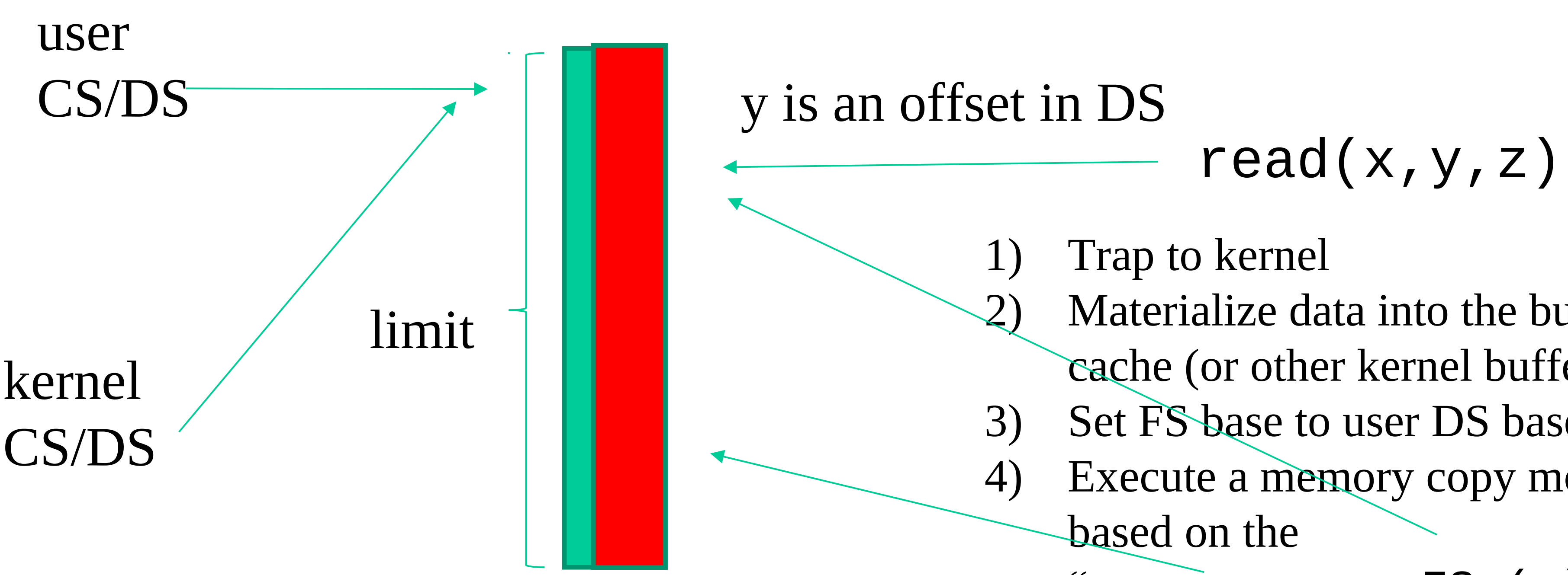
`read(x,y,z)`

1) Trap to kernel
2) Materialize data to be delivered into the buffer cache (or other kernel buffers)
3) Set FS base to user DS base
4) Execute a memory copy module based on the “`mov source, FS:(y)`” pattern
5) Restore FS to the original content

The case of “constrained” segmentation

- This is x86 long mode segmentation
- This is also x86 protected mode with classical mapping of user/kernel CS, DS, SS, ES to base 0x0
- Making FS to point to the base of “user DS” does not work (it fails)
- The offset ‘y’ will still apply to kernel DS
- Hence the “`mov source, FS:(y)`” construct may lead to write kernel level memory pages, depending on the value of ‘y’

A representation of the failure



1) Trap to kernel
2) Materialize data into the buffer cache (or other kernel buffers)
3) Set FS base to user DS base
4) Execute a memory copy module based on the “`mov source, FS:(y)`” pattern
5) Restore FS to the original content

Actual solutions with constrained segmentation

- Where to point for a user/kernel data exchange operation is not only defined by the processor state (and its relation to parameters passed to the kernel)
- It is determined by the kernel software
- The determination is actuated <u>per each individual address space the kernel is managing</u>
- Hence each thread has its limitations on where pointers can be redirected for user/kernel data move
- When an operation is requested, the data move fixup inspects the per-thread limitations to determine if the operation is “legitim”

Per-thread memory limits in Linux

- Each thread management metadata keep a field called `addr_limit`
- It is embedded into a struct (in a field called `seg`) which can be read via the kernel API `get_fs()`
- <u>It can also be updated</u> to a generic value 'x' via the kernel API `set_fs(x)`
- All the kernel services that implement user/kernel data move make a check on `addr_limit`
- If the memory area (based on passed pointer and size of the destination/source buffer) is not within `addr_limit` the service does not (or partially) perform(s) memory copy

Example of `addr_limit` read

```
unsigned long limit;
......
limit = (unsigned long)get_fs().seg;
printk("limit is %p\n", limit);
```

Currently the limit in Linux is set to `0x00007ffffffff000` which is the lower half of the x86 long mode canonical addressing form

addr_limit update vs security

- Updates of `addr_limit` are typically infrequent (if not executed at all) operations
- At the same time enabling the update of `addr_limit` allows a thread to execute highly critical tasks (read/write) related to the access to kernel level zones
- The current plan in Linux is the one of eliminating this value from updatable thread management data
- <u>The limit will be then identified on the basis of a non-modifiable compile time defined value</u>

User/kernel level data move API

```
unsigned long copy_from_user(void *to, const void *from,
    unsigned long n)
```

Copies n bytes from the user address(from) to the kernel address space(to).

```
unsigned long copy_to_user(void *to, const void *from, unsigned
    long n)
```

Copies n bytes from the kernel address(from) to the user address space(to).

```
void get_user(void *to, void *from)
```

Copies an integer value from userspace (from) to kernel space (to).

```
void put_user(void *from, void *to)
```

Copies an integer value from kernel space (from) to userspace (to).

User/kernel level data move API

```
long strncpy_from_user(char *dst, const char *src, long count)
```

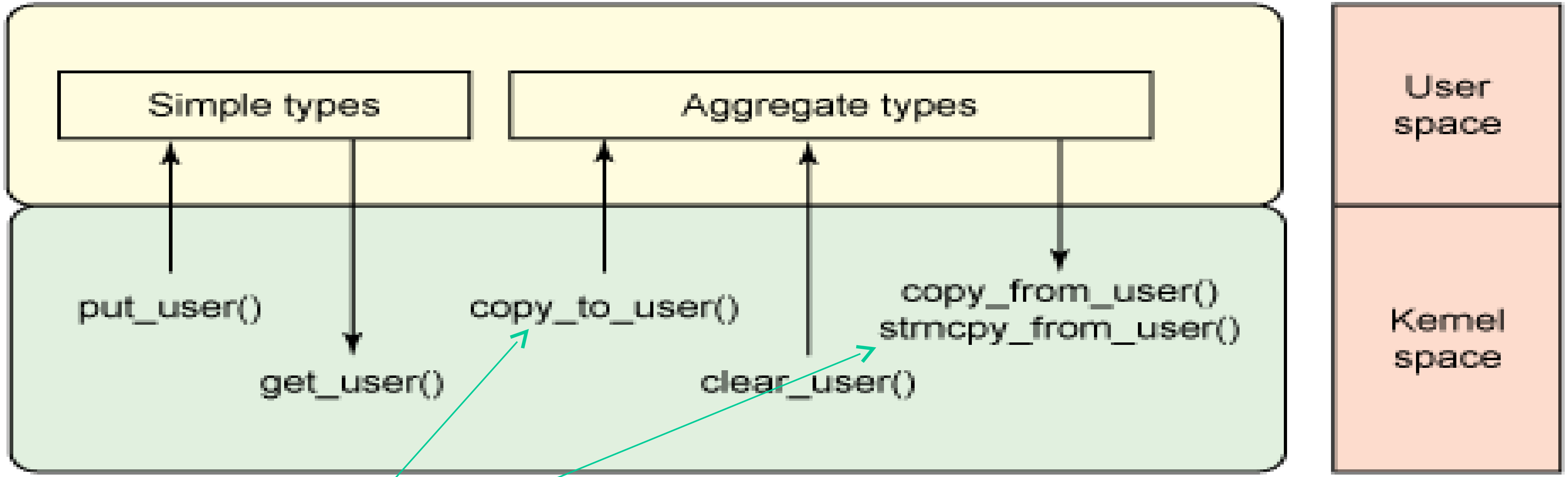
Copies a null terminated string of at most count bytes long from userspace (src) to kernel space (dst)

```
int access_ok(int type, unsigned long addr, unsigned long size)
```

Returns nonzero if the userspace block of memory is valid and zero otherwise

These data move operations may "memory fail" but limited to already mapped regions – the results returned indicates the residual bytes of the data move operation, not the amount of data actually moved

A scheme



These functions return the residuals (bytes not managed)

Most of them ground on `access_ok()`

The actual copy operation may lead the thread to sleep
(we will be back to this issue when talking of contexts)

Overall view of the API actions

- Segment fixup (if segmentation takes a real role in the composition of the addresses)

- Check on address ranges related to user level

  - ✓ The actual depth of check may depend on the specific implementation (namely on the kernel version)

  - ✓ E.g., the process memory map might be checked or not

- <u>**Note:**</u> associating physical to virtual memory is demanded to the page-fault handler

  - ✓ Performance impact due to (possible) non-atomicity while finalizing the handling

Service redundancy approaches

- Check and fixup are required only in case we need to link activities across different privilege levels within the ring model (as when calling system calls)

- Particularly, this occurs when the execution semantic crosses the boundaries of individual segments

- <u>Bypassing check e fixup</u> when no crossing of segment boundaries occurs takes place via “service redundancy” (for performance reasons)

- The kernel layer entails an internal API for executing activities that are typically triggered when running in user mode

Classical examples

- `kernel_read()` is a redundancy for `read()`
- `kernel_write()` is a redundancy for `write()`

`read() – syscall`

`sys_read()`

`read()` – file operation
real data movement

This requires
fixup with
possible update of
`addr_limit`

call from the kernel

`kernel_read()`

`memcpy` with tampered pointers

- Clearly, the usage of fixup based APIs for data movement does not break the ring model under normal operating conditions
- What if a `memcpy()` is called by the kernel, with arbitrary pointers after a subversion (speculative or not) or in presence of bugs?
- In more dated processor/kernel versions we could do nothing
- In more modern processors/kernels we have ad additional security oriented hardware support, which leads to **<u>constrained supervisor mode</u>**!!

The actual hardware support on x86

- SMAP (Supervisor Mode Access Prevention)
  - ✓ It blocks data access to user pages when running at CPL 0
- SMEP (Supervisor Mode Execution Prevention)
  - ✓ It blocks instruction fetches from user pages when running at CPL 0
- Two bits in CR4 (21 and 20) activate them
- They can be temporary disabled (e.g. setting the AC bit in EFLAGS for the case of SMAP)

`copy_to_user` timeline (as a reference example)

- Check within per-thread limit
- <u>Determine the legal amount of data to be copied</u>
- Disable SMAP (via the AC flag through the `stac` x86 instruction)
- Make the copy (<u>may wait but not SEGFAULT</u>)
- Enable SMAP again (via the AC flag through the `clac` x86 instruction

`access_OK` limitations

- The determination of the legal amount of data to be copied requires inspecting the memory map (via `*mm`) of the running thread
- Various additional machine instructions used just to move data between kernel and user
    - Interactions with suboptimal usage of I/O services (e.g. byte rather than segment reads/writes)
- `mm` inspection may have linear (non-constant) cost

Newer approaches - kernel masked SEGFAULTS

- Access OK control only checks the `addr_limit`
- If `addr_limit` is OK then the memory copy is directly executed
- **If and only if** some user page not mapped (or not compliant with the protection requested by the memory copy) is touched we have a SEGFAULT from kernel software (RIP points to a kernel page)
- The philosophy is the one of speeding up the normal scenario

Kernel masked SEGFAULTS details

	Segfaulting RIP	**Alternative RIP**
`copy_to_user`	A	A′
……		
`put_user`	B	B’

The page fault handler check this table and passes control to the alternative block of code

Known at kernel compile/load time

The alternative code block finalizes the data move simply returning the residual bytes number