Outline

Some complications of paging

- **What happens to available memory?**
  - Some physical memory tied up by kernel VM structures
  - E.g., page tables, page metadata
- **What happens to user/kernel crossings?**
  - More crossings into kernel
  - Pointers in syscall arguments must be checked
    (can't just kill process if page not present—might need to page in)
- **What happens to IPC?**
  - Must change hardware address space
  - Increases TLB misses
  - Context switch flushes TLB entirely on old x86 machines
    (But not on MIPS. . . Why?)

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    (But not on MIPS…Why? MIPS tags TLB entries with PID)

64-bit address spaces

- **Recall x86-64 only has 48-bit virtual address space**
- **What if you want a 64-bit virtual address space?**
  - Straight hierarchical page tables not efficient
  - But software TLBs (like MIPS) allow other possibilities
- **Solution 1: Hashed page tables**
  - Store Virtual $\rightarrow$ Physical translations in hash table
  - Table size proportional to physical memory
  - Clustering makes this more efficient [Talluri]
- **Solution 2: Guarded page tables [Liedtke]**
  - Omit intermediary tables with only one entry
  - Add predicate in high level tables, stating the only virtual address range mapped underneath + # bits to skip

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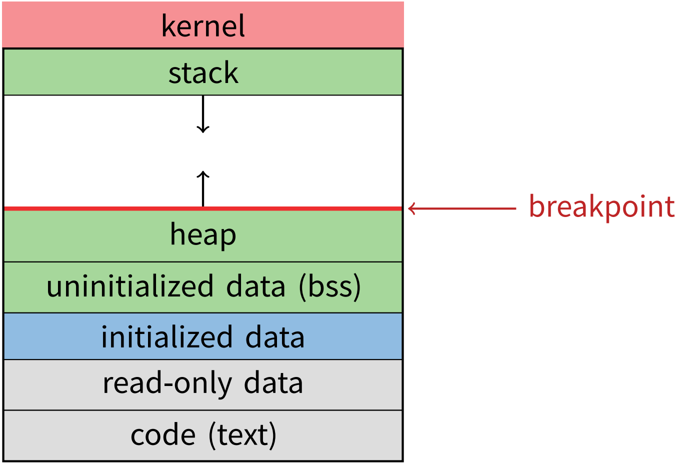
2. The user-level perspective
3. Case study: 4.4 BSD

Recall typical virtual address space

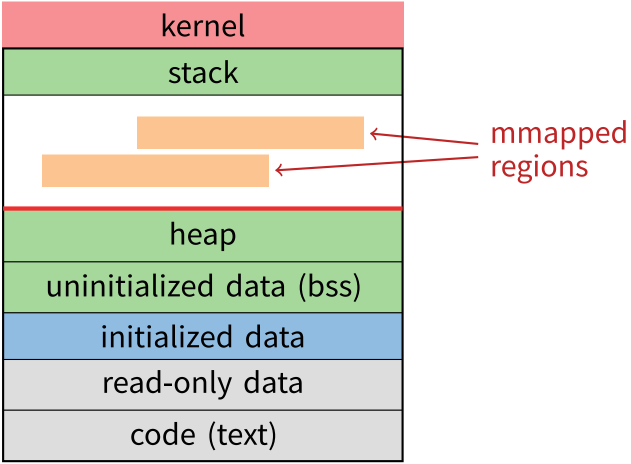


- **Dynamically allocated memory goes in heap**
- **Top of heap called *breakpoint***
  - Addresses between breakpoint and stack all invalid

Early VM system calls

- **OS keeps "Breakpoint" – top of heap**
  - Memory regions between breakpoint & stack fault on access
- `char *brk (const char *addr);`
  - Set and return new value of breakpoint
- `char *sbrk (int incr);`
  - Increment value of the breakpoint & return old value
- **Can implement** `malloc` **in terms of** `sbrk`
  - But hard to "give back" physical memory to system

Memory mapped files



- **Other memory objects between heap and stack**

mmap system call

- `void *mmap (void *addr, size_t len, int prot,`
  `int flags, int fd, off_t offset)`
  - Map file specified by `fd` at virtual address `addr`
  - If `addr` is NULL, let kernel choose the address
- `prot` – **protection of region**
  - PROT_EXEC – executable
  - PROT_READ – readable
  - PROT_WRITE – writable
  - PROT_NONE – inaccessible
- `flags`
  - MAP_ANON – anonymous memory (`fd` should be -1)
  - MAP_PRIVATE – modifications are private
  - MAP_SHARED – modifications seen by everyone

More VM system calls

- `int msync(void *addr, size_t len, int flags);`
  - Flush changes of mmapped file to backing store
- `int munmap(void *addr, size_t len)`
  - Removes memory-mapped object
- `int mprotect(void *addr, size_t len, int prot)`
  - Changes protection on pages to or of `PROT_...`
- `int mincore(void *addr, size_t len, char *vec)`
  - Returns in `vec` which pages present
- `int madvise(void *addr, size_t len, int advice);`
  - Advises the OS regarding the memory behavior
  - `MADV_FREE` – Kernel can discard the memory
  - `MADV_WILLNEED` – Will need the memory soon
  - `MADV_DONTNEED` – Kernel can swap the memory
  - `MADV_NORMAL`, `MADV_SEQUENTIAL`, `MADV_RANDOM` – Hint access pattern

Exposing page faults

- *Signals* are a mechanism to receive notifications from the kernel
- You can think of these as userspace exceptions

```
struct sigaction {
  union {                /* signal handler */
    void (*sa_handler)(int);
    void (*sa_sigaction)(int, siginfo_t *, void *);
  };
  sigset_t sa_mask;     /* signal mask to apply */
  int sa_flags;
};

int sigaction (int sig, const struct sigaction *act,
               struct sigaction *oact)
```

- Can specify function to run on `SIGSEGV`
  (Unix signal raised on invalid memory access)

Example: OpenBSD/i386 siginfo

```
struct sigcontext {
  int sc_gs; int sc_fs; int sc_es; int sc_ds;
  int sc_edi; int sc_esi; int sc_ebp; int sc_ebx;
  int sc_edx; int sc_ecx; int sc_eax;

  int sc_eip; int sc_cs; /* instruction pointer */
  int sc_eflags;         /* condition codes, etc. */
  int sc_esp; int sc_ss; /* stack pointer */

  int sc_onstack;        /* sigstack state to restore */
  int sc_mask;           /* signal mask to restore */

  int sc_trapno;
  int sc_err;
};
```

- **Linux uses `ucontext_t` – same idea, just uses nested structures that won't all fit on one slide**

VM tricks at user level

- **Combination of `mprotect`/`sigaction` very powerful**
  - Can use OS VM tricks in user-level programs [Appel&Li]
  - E.g., fault, unprotect page, return from signal handler
- **Technique used in object-oriented databases**
  - Bring in objects on demand
  - Keep track of which objects may be dirty
  - Manage memory as a cache for much larger object DB
- **Other interesting applications**
  - Useful for some garbage collection algorithms
  - Snapshot processes (copy on write)

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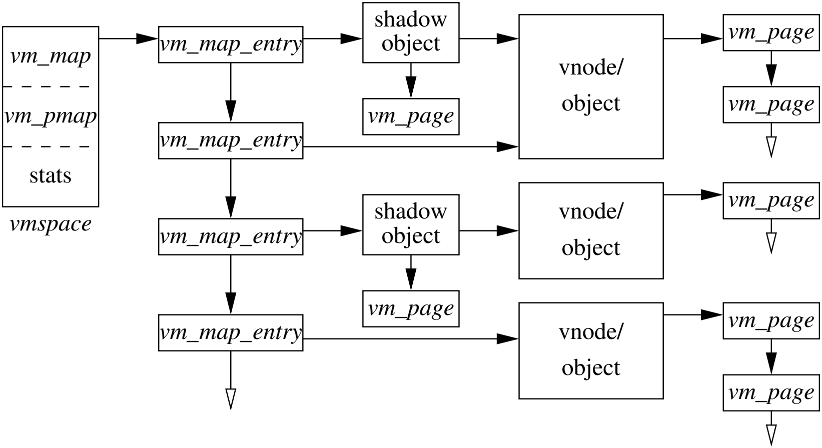
4.4 BSD VM system [McKusick]

- **Each process has a *vmspace* structure containing**
  - *vm_map* – machine-independent virtual address space
  - *vm_pmap* – machine-dependent data structures
  - statistics – e.g. for syscalls like *getrusage ()*
- ***vm_map* is a linked list of *vm_map_entry* structs**
  - *vm_map_entry* covers contiguous virtual memory
  - points to *vm_object* struct
- ***vm_object* is source of data**
  - e.g. vnode object for memory mapped file
  - points to list of *vm_page* structs (one per mapped page)
  - *shadow objects* point to other objects for copy on write

4.4 BSD VM data structures



Pmap (machine-dependent) layer

- **Pmap layer holds architecture-specific VM code**
- **VM layer invokes pmap layer**
  - On page faults to install mappings
  - To protect or unmap pages
  - To ask for dirty/accessed bits
- **Pmap layer is lazy and can discard mappings**
  - No need to notify VM layer
  - Process will fault and VM layer must reinstall mapping
- **Pmap handles restrictions imposed by cache**

Example uses

- ***vm_map_entry*** **structs for a process**
  - r/o text segment $\rightarrow$ file object
  - r/w data segment $\rightarrow$ shadow object $\rightarrow$ file object
  - r/w stack $\rightarrow$ anonymous object
- **New *vm_map_entry* objects after a fork:**
  - Share text segment directly (read-only)
  - Share data through two new shadow objects (must share pre-fork but not post-fork changes)
  - Share stack through two new shadow objects
- **Must discard/collapse superfluous shadows**
  - E.g., when child process exits

What happens on a fault?

- **Traverse *vm_map_entry* list to get appropriate entry**
  - No entry? Protection violation? Send process a SIGSEGV
- **Traverse list of [shadow] objects**
- **For each object, traverse *vm_page* structs**
- **Found a *vm_page* for this object?**
  - If first *vm_object* in chain, map page
  - If read fault, install page read only
  - Else if write fault, install copy of page
- **Else get page from object**
  - Page in from file, zero-fill new page, etc.

Paging in day-to-day use

- **Demand paging**
  - Read pages from *vm_object* of executable file
- **Copy-on-write (`fork`, `mmap`, etc.)**
  - Use shadow objects
- **Growing the stack, BSS page allocation**
  - A bit like copy-on-write for `/dev/zero`
  - Can have a single read-only zero page for reading
  - Special-case write handling with pre-zeroed pages
- **Shared text, shared libraries**
  - Share *vm_object* (shadow will be empty where read-only)
- **Shared memory**
  - Two processes `mmap` same file, have same *vm_object* (no shadow)