• Use disk to simulate larger virtual than physical mem
Working set model

- Disk much, much slower than memory
  - Goal: run at memory speed, not disk speed

- 80/20 rule: 20% of memory gets 80% of memory accesses
  - Keep the hot 20% in memory
  - Keep the cold 80% on disk
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Paging challenges

- How to resume a process after a fault?
  - Need to save state and resume
  - Process may have been in the middle of an instruction!

- What to fetch from disk?
  - Just needed page or more?

- What to eject?
  - How to allocate physical pages amongst processes?
  - Which of a particular process’s pages to keep in memory?
Re-starting instructions

- Hardware must allow resuming after a fault
- Hardware provides kernel with information about page fault
  - Faulting virtual address (In %cr2 reg on x86—may see it if you modify Pintos page_fault and use fault_addr)
  - Address of instruction that caused fault
  - Was the access a read or write? Was it an instruction fetch? Was it caused by user access to kernel-only memory?
- Observation: Idempotent instructions are easy to restart
  - E.g., simple load or store instruction can be restarted
  - Just re-execute any instruction that only accesses one address
- Complex instructions must be re-started, too
  - E.g., x86 move string instructions
  - Specify src, dst, count in %esi, %edi, %ecx registers
  - On fault, registers adjusted to resume where move left off
What to fetch

• Bring in page that caused page fault
• Pre-fetch surrounding pages?
  - Reading two disk blocks approximately as fast as reading one
  - As long as no track/head switch, seek time dominates
  - If application exhibits spacial locality, then big win to store and read multiple contiguous pages
• Also pre-zero unused pages in idle loop
  - Need 0-filled pages for stack, heap, anonymously mmapped memory
  - Zeroing them only on demand is slower
  - Hence, many OSes zero freed pages while CPU is idle
Selecting physical pages

- May need to eject some pages
  - More on eviction policy in two slides
- May also have a choice of physical pages
- Direct-mapped physical caches (older machines)
  - Physical address $A$ conflicts with $kC + A$
    (where $k$ is any integer, $C$ is cache size)
  - Virtual $\rightarrow$ Physical mapping can affect performance
  - Applications can conflict with each other or themselves
  - Scientific applications benefit if consecutive virtual pages do not conflict in the cache
  - Many other applications do better with random mapping
- Set associative caches (more common)
  - Multiple (e.g., 2–4) possible slots for each physical address
  - Historically $n$-way associative cache chooses line by $A \mod (C/n)$
  - These days: CPUs use more sophisticated mapping [Hund]
• How should OS make use of “large” mappings
  - x86 has 2/4MiB pages that might be useful
  - Alpha has even more choices: 8KiB, 64KiB, 512KiB, 4MiB

• Sometimes more pages in L2 cache than TLB entries
  - Don’t want costly TLB misses going to main memory
  - Try `cpuid` tool to find CPU’s TLB configuration on Linux…
    then compare to cache size reported by `lscpu`

• Or have two-level TLBs
  - Want to maximize hit rate in faster L1 TLB

• OS can transparently support superpages [Navarro]
  - “Reserve” appropriate physical pages if possible
  - Promote contiguous pages to superpages
  - Does complicate evicting (esp. dirty pages) – demote
Outline

1. Paging
2. Eviction policies
3. Thrashing
4. Details of paging
5. The user-level perspective
6. Case study: 4.4 BSD
Straw man: FIFO eviction

- Evict oldest fetched page in system
- Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- 3 physical pages: 9 page faults
Straw man: FIFO eviction

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- Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- 3 physical pages: 9 page faults
- 4 physical pages: 10 page faults

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10 page faults
Belady’s Anomaly

- More physical memory doesn’t always mean fewer faults
What is optimal (if you knew the future)?

- Replace page that will not be used for longest period of time

Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

With 4 physical pages:
Optimal page replacement

• What is optimal (if you knew the future)?
  - Replace page that will not be used for longest period of time

• Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

• With 4 physical pages:

  1 4
  2
  3
  4 5

  6 page faults

• What do we do when an OS can’t predict the future?
LRU page replacement

• Approximate optimal with *least recently used*
  - Because past often predicts the future

• Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

• With 4 physical pages: 8 page faults

```
1  5
2
3  5  4
4  3
```

• Problem 1: Can be pessimal – example?

• Problem 2: How to implement?
LRU page replacement

- Approximate optimal with *least recently used*
  - Because past often predicts the future
- Example—reference string 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- With 4 physical pages: 8 page faults

```
  1 5
  2
  3 5 4
  4 3
```

- Problem 1: Can be pessimal – example?
  - Looping over memory (then want MRU eviction)
- Problem 2: How to implement?
Straw man LRU implementations

- **Stamp PTEs with timer value**
  - E.g., CPU has cycle counter
  - Automatically writes value to PTE on each page access
  - Scan page table to find oldest counter value = LRU page
  - Problem: Would double memory traffic!

- **Keep doubly-linked list of pages**
  - On access remove page, place at tail of list
  - Problem: again, very expensive

- **What to do?**
  - Just approximate LRU, don’t try to do it exactly
Clock algorithm

- Use accessed bit supported by most hardware
  - E.g., x86 will write 1 to A bit in PTE on first access
  - Software managed TLBs like MIPS can do the same

- Do FIFO but skip accessed pages
- Keep pages in circular FIFO list
- Scan:
  - page’s A bit = 1, set to 0 & skip
  - else if A = 0, evict

- A.k.a. second-chance replacement
Clock algorithm

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Clock algorithm (continued)

- Large memory may be a problem
  - Most pages referenced in long interval

- Add a second clock hand
  - Two hands move in lockstep
  - Leading hand clears $A$ bits
  - Trailing hand evicts pages with $A=0$

- Can also take advantage of hardware Dirty bit
  - Each page can be (Unaccessed, Clean), (Unaccessed, Dirty), (Accessed, Clean), or (Accessed, Dirty)
  - Consider clean pages for eviction before dirty

- Or use $n$-bit accessed count instead just $A$ bit
  - On sweep: $count = (A \ll (n-1)) | (count \gg 1)$
  - Evict page with lowest count
Clock algorithm (continued)

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- Or use $n$-bit accessed $count$ instead just $A$ bit
  - On sweep: $count = (A \ll (n - 1)) \mid (count \gg 1)$
  - Evict page with lowest $count$
Other replacement algorithms

- **Random eviction**
  - Dirt simple to implement
  - Not overly horrible (avoids Belady & pathological cases)

- **LFU (least frequently used) eviction**
  - Instead of just A bit, count # times each page accessed
  - Least frequently accessed must not be very useful (or maybe was just brought in and is about to be used)
  - Decay usage counts over time (for pages that fall out of usage)

- **MFU (most frequently used) algorithm**
  - Because page with the smallest count was probably just brought in and has yet to be used

- Neither LFU nor MFU used very commonly
Naïve paging

- Naïve page replacement: 2 disk I/Os per page fault
Page buffering

- **Idea**: reduce # of I/Os on the critical path

- **Keep pool of free page frames**
  - On fault, still select victim page to evict
  - But read fetched page into already free page
  - Can resume execution while writing out victim page
  - Then add victim page to free pool

- **Can also yank pages back from free pool**
  - Contains only clean pages, but may still have data
  - If page fault on page still in free pool, recycle
• **Allocation can be** _global_ or _local_

• **Global allocation** doesn’t consider page ownership
  - E.g., with LRU, evict least recently used page of any proc
  - Works well if $P_1$ needs 20% of memory and $P_2$ needs 70%:

  ![Diagram showing memory allocation]

  - Doesn’t protect you from memory pigs
    (imagine $P_2$ keeps looping through array that is size of mem)

• **Local allocation isolates processes (or users)**
  - Separately determine how much memory each process should have
  - Then use LRU/clock/etc. to determine which pages to evict within each process
1. Paging
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Thrashing

- Processes require more memory than system has
  - Each time one page is brought in, another page, whose contents will soon be referenced, is thrown out
  - Processes will spend all of their time blocked, waiting for pages to be fetched from disk
  - Disk at 100% utilization, but system not getting much useful work done

- What we wanted: virtual memory the size of disk with access time the speed of physical memory

- What we got: memory with access time of disk
Reasons for thrashing

- Access pattern has no temporal locality (past $\neq$ future)
  - (80/20 rule has broken down)

- Hot memory does not fit in physical memory

- Each process fits individually, but too many for system
  - At least this case is possible to address
• Must shed load when thrashing
Dealing with thrashing

• **Approach 1: working set**
  - Thrashing viewed from a caching perspective: given locality of reference, how big a cache does the process need?
  - Or: how much memory does the process need in order to make reasonable progress (its working set)?
  - Only run processes whose memory requirements can be satisfied

• **Approach 2: page fault frequency**
  - Thrashing viewed as poor ratio of fetch to work
  - PFF = page faults / instructions executed
  - If PFF rises above threshold, process needs more memory. Not enough memory on the system? Swap out.
  - If PFF sinks below threshold, memory can be taken away
- Working set changes across phases
  - Balloons during phase transitions
Calculating the working set

- **Working set**: all pages that process will access in next $T$ time
  - Can’t calculate without predicting future
- **Approximate by assuming past predicts future**
  - So working set $\approx$ pages accessed in last $T$ time
- **Keep idle time for each page**
- **Periodically scan all resident pages in system**
  - A bit set? Clear it and clear the page’s idle time
  - A bit clear? Add CPU consumed since last scan to idle time
  - Working set is pages with idle time $< T$
Two-level scheduler

- **Divide processes into** active & inactive
  - Active – means working set resident in memory
  - Inactive – working set intentionally not loaded

- **Balance set: union of all active working sets**
  - Must keep balance set smaller than physical memory

- **Use long-term scheduler [recall from lecture 4]**
  - Moves procs active → inactive until balance set small enough
  - Periodically allows inactive to become active
  - As working set changes, must update balance set

- **Complications**
  - How to chose idle time threshold $T$?
  - How to pick processes for active set
  - How to count shared memory (e.g., libc.so)
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Some complications of paging

- **What happens to available memory?**
  - Some physical memory tied up by kernel VM structures

- **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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- **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? 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 → 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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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

- Kernel
- Stack
- Heap
- Uninitialized data (bss)
- Initialized data
- Read-only data
- Code (text)

- 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
  - OR of PROT_EXEC, PROT_READ, PROT_WRITE, PROT_NONE

- 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 bitwise or of some PROT_...values
- **int mincore(void *addr, size_t len, char *vec)**
  - Returns in vec which pages present
Exposing page faults

```
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)
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]
  - 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)
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

---

¹Use link on [searchworks page](https://searchworks) for access
**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 → file object
  - r/w data segment → shadow object → file object
  - r/w stack → 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)