- Use disk to simulate larger virtual than physical mem
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
Disk much, much slower than memory
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• 80/20 rule: 20% of memory gets 80% of memory accesses
  - Keep the hot 20% in memory
  - Keep the cold 80% on disk
Paging challenges

- **How to resume a process after a fault?**
  - Need to save state and resume
  - Process might 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 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?

- Hardware must allow resuming after a fault

- Idempotent instructions are easy
  - 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
  - Virtual → Physical mapping can affect performance
  - In old days: Physical address $A$ conflicts with $kC + A$
    (where $k$ is any integer, $C$ is cache size)
  - 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
  - These days: CPUs more sophisticated than $kC + A$
Superpages

- How should OS make use of “large” mappings
  - x86 has 2/4MB pages that might be useful
  - Alpha has even more choices: 8KB, 64KB, 512KB, 4MB

- Sometimes more pages in L2 cache than TLB entries
  - Don’t want costly TLB misses going to main memory

- 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
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

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9 page faults
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
- 4 physical pages: 10 page faults

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Belady’s Anomaly

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

Problem 1: Can be pessimal – example?

Problem 2: How to implement?
• **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., Pentium 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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Clock algorithm (continued)

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- Or use $n$-bit accessed count instead just $A$ bit
  - On sweep: $\text{count} = (A \ll (n - 1)) | (\text{count} \gg 1)$
  - Evict page with lowest $\text{count}$
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%:
    - 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
Outline

1. Paging
2. Eviction policies
3. Thrashing
4. Details of paging
5. The user-level perspective
6. Case study: 4.4 BSD
UNSAFE AT ANY SPEED
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
  - I/O devs 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)

![Graph showing access pattern]

(80/20 rule has broken down)

- Hot memory does not fit in physical memory

![Diagram showing memory usage]

- Each process fits individually, but too many for system

![Diagram showing process allocation]

- At least this case is possible to address
Multiprogramming & Thrashing

- 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 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 $\rightarrow$ 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)
1. Paging
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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?)
Some complications of paging

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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 $\rightarrow$ 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
1. Paging
2. Eviction policies
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6. 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

- 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
• 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
Exposing page faults

```c
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)
1. Paging
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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
• **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)