Putting it all together

- **Relocation** using Base and Limit registers
 - simple, but inflexible

• Segmentation:

- compiler's view presented to OS
- segment tables tend to be small
- memory allocation is expensive and complicated (first fit, worst fit, best fit).
- compaction is needed to resolve external fragmentation.



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Putting it all together

• Paging:

- simplifies memory allocation since any page can be allocated to any frame
- page tables can be very large (especially when virtual address space is large and pages are small)

Segmentation & Paging

- only need to allocate as many page table entries as we need (large virtual address spaces are not a problem).
- easy memory allocation, any frame can be used
- sharing at either the page or segment level
- increased internal fragmentation over paging
- two lookups per memory reference



Today: Demand Paged Virtual Memory

- Up to now, the virtual address space of a process fit in memory, and we assumed it was all in memory.
- OS illusions:
 - 1. treat disk (or other backing store) as a much larger, but much slower main memory
 - 2. analogous to the way in which main memory is a much larger, but much slower, cache or set of registers
- The illusion of an infinite virtual memory enables
 - 1. a process to be larger than physical memory, and
 - 2. a process to execute even if all of the process is not in memory
 - 3. Allow more processes than fit in memory to run concurrently.



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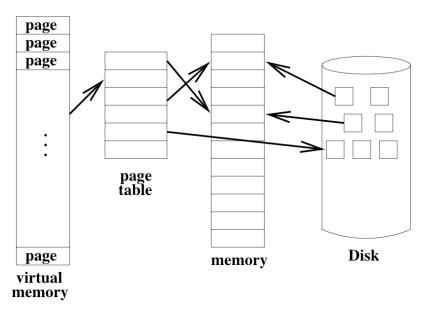
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Demand Paged Virtual Memory

- Demand Paging uses a memory as a cache for the disk
- The page table (memory map) indicates if the page is on disk or memory using a valid bit
- Once a page is brought from disk into memory, the OS updates the page table and the valid bit
- For efficiency reasons, memory accesses must reference pages that are in memory the vast majority of the time
 - Else the effective memory access time will approach that of the disk
- **Key Idea:** Locality---the *working set* size of a process must fit in memory, and must stay there. (90/10 rule.)



Demand Paged Virtual Memory





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When to load a page?

- At process start time: the virtual address space must be no larger than the physical memory.
- Overlays: application programmer indicates when to load and remove pages.
 - Allows virtual address space to be larger than physical address space
 - Difficult to do and is error-prone
- **Request paging:** process tells an OS before it needs a page, and then when it is through with a page.



When to load a page?

- **Demand paging:** OS loads a page the first time it is referenced.
 - May remove a page from memory to make room for the new page
 - Process must give up the CPU while the page is being loaded
 - Page-fault: interrupt that occurs when an instruction references a page that is not in memory.
- **Pre-paging:** OS guesses in advance which pages the process will need and pre-loads them into memory
 - Allows more overlap of CPU and I/O if the OS guesses correctly.
 - If the OS is wrong => page fault
 - Errors may result in removing useful pages.
 - Difficult to get right due to branches in code.



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Implementation of Demand Paging

- A copy of the entire program must be stored on disk. (Why?)
- Valid bit in page table indicates if page is in memory.
 - 1: in memory 0: not in memory (either on disk or bogus address)
- If the page is not in memory, trap to the OS on first the reference
- The OS checks that the address is valid. If so, it
 - 1. selects a page to replace (page replacement algorithm)
 - 2. invalidates the old page in the page table
 - 3. starts loading new page into memory from disk
 - 4. context switches to another process while I/O is being done
 - 5. gets interrupt that page is loaded in memory
 - 6. updates the page table entry
 - 7. continues faulting process (why not continue current process?)



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Swap Space

- What happens when a page is removed from memory?
 - If the page contained code, we could simply remove it since it can be reloaded from the disk.
 - If the page contained data, we need to save the data so that it can be reloaded if the process it belongs to refers to it again.
 - Swap space: A portion of the disk is reserved for storing pages that are evicted from memory
- At any given time, a page of virtual memory might exist in one or more of:
 - The file system
 - Physical memory
 - Swap space
- Page table must be more sophisticated so that it knows where to find a page



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Performance of Demand Paging

- Theoretically, a process could access a new page with each instruction.
- Fortunately, processes typically exhibit *locality of reference*
 - Temporal locality: if a process accesses an item in memory, it will tend to reference the same item again soon.
 - Spatial locality: if a process accesses an item in memory, it will tend to reference an adjacent item soon.
- Let *p* be the probability of a page fault $(0 \le p \le 1)$.
- Effective access time = $(1-p) \times ma + p \times page$ fault time
 - If memory access time is 200 ns and a page fault takes 25 ms
 - Effective access time = $(1-p) \times 200 + p \times 25,000,000$
- If we want the effective access time to be only 10% slower than memory access time, what value must p have?



Updating the TLB

- In some implementations, the hardware loads the TLB on a TLB miss.
- If the TLB hit rate is very high, use software to load the TLB
 - 1. Valid bit in the TLB indicates if page is in memory.
 - 2. on a TLB hit, use the frame number to access memory
 - 3. trap on a TLB miss, the OS then
 - a) checks if the page is in memory
 - b) if page is in memory, OS picks a TLB entry to replace and then fills it in the new entry
 - c) if page is not in memory, OS picks a TLB entry to replace and fills it in as follows
 - i. invalidates TLB entry
 - ii. perform page fault operations as described earlier
 - iii. updates TLB entry
 - iv. restarts faulting process

All of this is still functionally transparent to the user.



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Transparent Page Faults

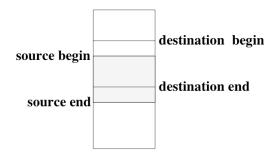
How does the OS transparently restart a faulting instruction?

- Need hardware support to save
 - 1. the faulting instruction,
 - 2. the CPU state.
- What about instructions with side-effects? (CISC)
 - mov a, (r10)+: moves a into the address contained in register 10 and increments register 10.
- Solution: unwind side effects



Transparent Page Faults

• Block transfer instructions where the source and destination overlap can't be undone.



 Solution: check that all pages between the starting and ending addresses of the source and destination are in memory before starting the block transfer



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Page Replacement Algorithms

On a page fault, we need to choose a page to evict

Random: amazingly, this algorithm works pretty well.

- **FIFO:** First-In, First-Out. Throw out the oldest page. Simple to implement, but the OS can easily throw out a page that is being accessed frequently.
- MIN: (a.k.a. OPT) Look into the future and throw out the page that will be accessed farthest in the future (provably optimal [Belady'66]). Problem?
- LRU: Least Recently Used. Approximation of MIN that works well if the recent past is a good predictor of the future. Throw out the page that has not been used in the longest time.



Example: FIFO

3 page Frames

4 virtual Pages: A B C D

Reference stream: A B C A B D A D B C B

FIFO: First-In-First-Out

	A	В	С	A	В	D	A	D	В	С	В
frame 1											
frame 2											
frame 3											

Number of page faults?



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Example: MIN

MIN: Look into the future and throw out the page that will be accessed farthest in the future.

	A	В	C	A	В	D	A	D	В	C	В
frame 1											
frame 2											
frame 3											

Number of page faults?



Example: LRU

•LRU: Least Recently Used. Throw out the page that has not been used in the longest time.

		A	В	C	A	В	D	A	D	В	C	В
	frame 1											
	<u> </u>											
	frame 2											
Number of page faults?	frame 3											



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Example: LRU

•When will LRU perform badly?

	A	В	C	A	В	D	A	D	В	C	В
frame 1											
frame 2											
frame 3											

Summary

Benefits of demand paging:

- Virtual address space can be larger than physical address space.
- Processes can run without being fully loaded into memory.
 - Processes start faster because they only need to load a few pages (for code and data) to start running.
 - Processes can share memory more effectively, reducing the costs when a context switch occurs.
- A good page replacement algorithm can reduce the number of page faults and improve performance



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