Virtual Memory (Part II)

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Reminder

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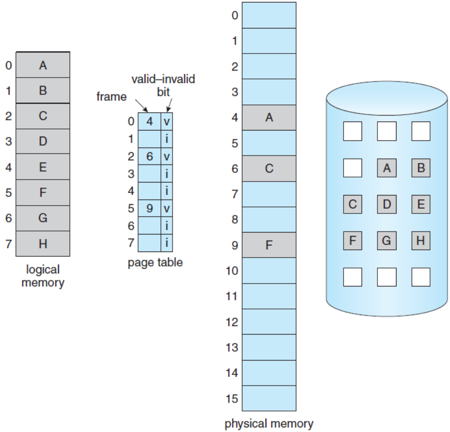
- Partially-loaded programs
- Virtual memory: much larger than physical memory



Reminder

- Demand paging similar to paging + swapping
- Locality
- Page fault
- Page replacement algorithms:
  - FIFO, optimal, LRU, LRU-approximate, counting-based

Allocation of Frames

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- If we have 93 free frames and two processes, how many frames does each process get?

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- Each process needs minimum number of frames.
  - Example: IBM 370: 6 pages to handle MOVE instruction:
  - Instruction is 6 bytes, might span 2 pages
  - 2 pages to handle from
  - 2 pages to handle to

Frame Allocation Constraints (2/2)

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- Decreases the number of frames:
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- When a page fault occurs before an executing instruction is complete, the instruction must be restarted.
  - We must have enough frames to hold all the different pages that any single instruction can reference.

Allocation Schemes

- Fixed allocation

- Priority allocation

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- Split m frames among n processes: $\frac{m}{n}$ frames to each process.
- Example, if there are 93 frames and 5 processes
  - Each process will get 18 frames.
  - The 3 leftover frames can be used as a free-frame buffer pool.

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- $a_i = \frac{s_i}{S} \times m$: allocation for p_i

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- Two processes:
  - A student process: 10KB
  - An interactive database: 127KB
- Equal allocation: $s_1 = 10, s_2 = 127, S = 137, m = 62$
- $a_1 = \frac{10}{137} \times 62 \approx 4$ $\qquad$ $a_2 = \frac{127}{137} \times 62 \approx 57$

Priority Allocation

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- If process p_i generates a page fault:
  - Select for replacement one of its frames.
  - Select for replacement a frame from a process with lower priority number.

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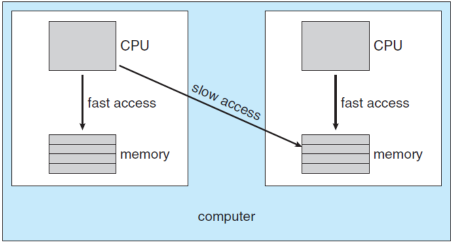
- Local replacement: each process selects from only its own set of allocated frames
  - More consistent per-process performance
  - Possibly underutilized memory

Non-Uniform Memory Access

- So far all memory accessed equally.
- Many systems are NUMA: speed of access to memory varies.



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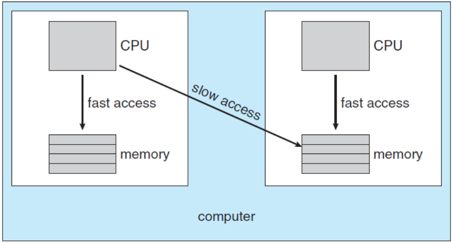

- Optimal performance: allocate memory close to the CPU on which the thread is scheduled.

Thrashing

Thrashing (1/2)

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  - Page fault to get page
  - Replace existing frame
  - But quickly need replaced frame back

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  - Page fault to get page
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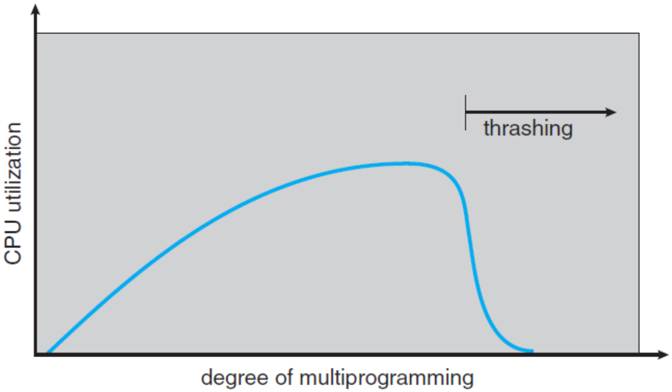
- This leads to:
  - Low CPU utilization
  - OS thinks it needs to increase the degree of multiprogramming
  - Another process added to the system

Thrashing (2/2)



- Thrashing: a process is busy swapping pages in and out.

Prevent Thrashing

- Providing a process with as many frames as it needs.

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- Providing a process with as many frames as it needs.
- How do we know how many frames it needs?

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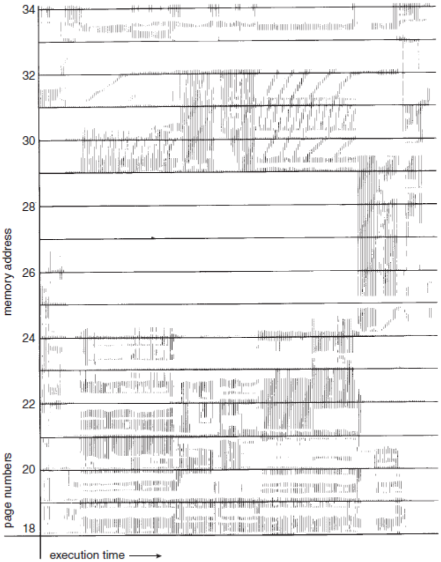
- A program is generally composed of several different localities, which may overlap.
- For example, when a function is called, it defines a new locality: consists of memory references to the instructions of the function call, its local variables, and a subset of the global variables.

Locality Model (2/2)



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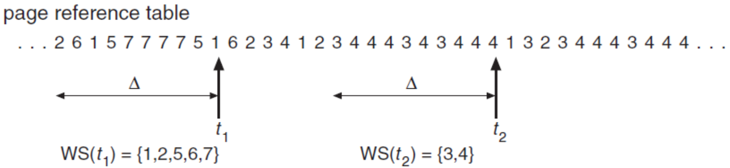
- After allocating all the pages of the locality, it will not fault again until it changes localities.
- If we do not allocate enough frames to accommodate the size of the current locality, the process will thrash.

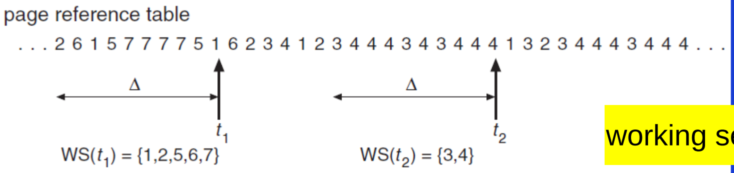
Working-Set Model (1/2)

- $\triangle$: working-set window: a fixed number of page references
- WSS_i: working set of process p_i: total number of pages referenced in the most recent $\triangle$ (varies in time).



Working-Set Model (1/2)

- △: working-set window: a fixed number of page references
- WSS_i: working set of process p_i: total number of pages referenced in the most recent △ (varies in time).
  - If △ too small will not encompass entire locality
  - If △ too large will encompass several localities
  - If $\triangle = \infty$ will encompass entire program



working set = 10

Working-Set Model (2/2)

- m: total number of frames

- D: total demand frames: $D = \sum WSS_i$:
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- Policy: if $D > m$, then suspend or swap out one of the processes.

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  - Timer interrupts after every 5000 time units.
  - Keep in memory 2 bits for each page.
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- Why is this not completely accurate?
- Improvement = 10 bits and interrupt every 1000 time units

Page-Fault Frequency

- More direct approach than WSS
- Establish acceptable page-fault frequency (PFF) rate and use local replacement policy
  - If actual rate too low, process loses frame
  - If actual rate too high, process gains frame

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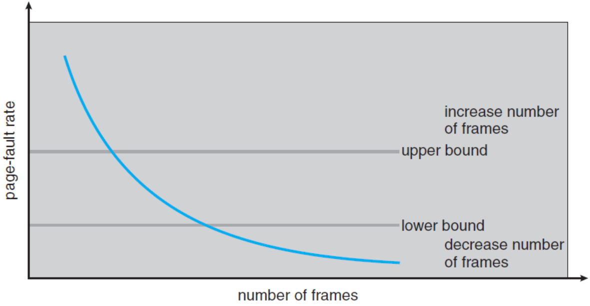

Working Sets and Page-Fault Rates

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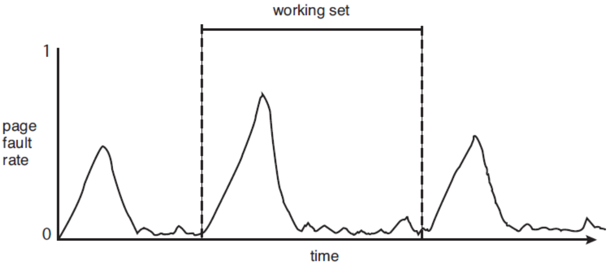
- Direct relationship between working set of a process and its page-fault rate.
- Working set changes over time.
- Peaks and valleys over time.



Allocating Kernel Memory

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- Often allocated from a free-memory pool
  - Kernel requests memory for structures of varying sizes
  - Some kernel memory needs to be contiguous, i.e. for I/O devices

Managing Free Memory Strategies

- Buddy system
- Slab allocation

Buddy System (1/2)

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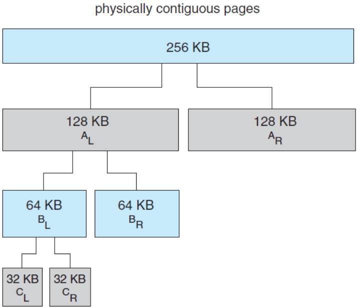
  - Continue until appropriate sized chunk available.

Buddy System (2/2)

- Assume 256KB chunk available, kernel requests 21KB.
  - Split into AL and AR of 128KB each.
  - One further divided into BL and BR of 64KB.
  - One further into CL and CR of 32KB each.



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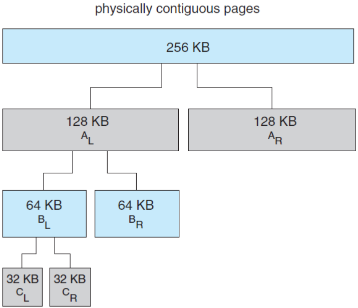
- Advantage: quickly coalesce unused chunks into larger chunk
- Disadvantage: fragmentation



Slab Allocation (1/2)

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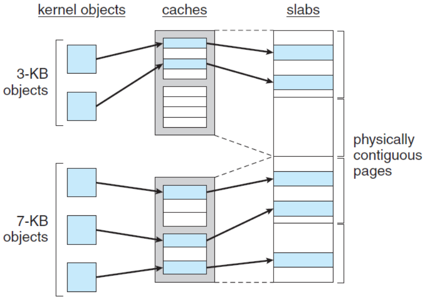

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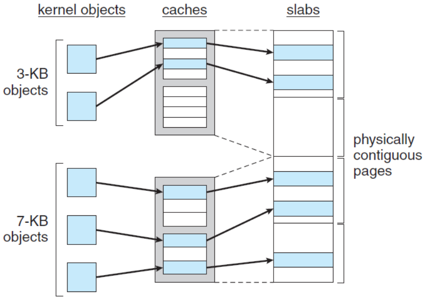

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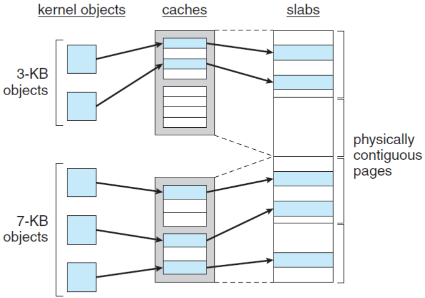

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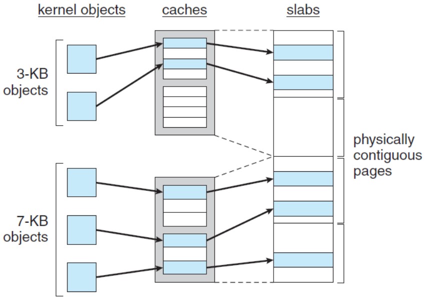
- Objects: instantiations of the data structure



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- If slab is full of used objects, next object allocated from empty slab.
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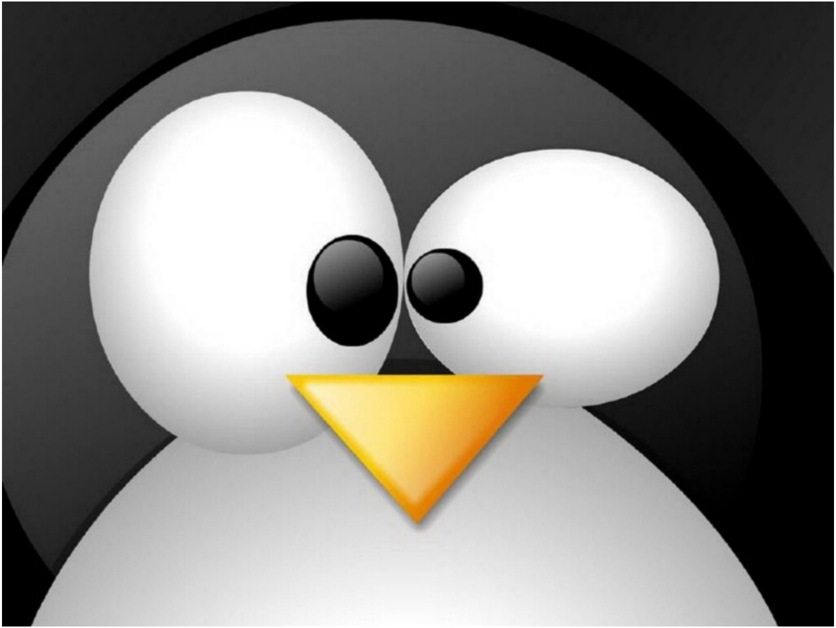
- Benefits include no fragmentation and fast memory request satisfaction.



Slab Allocator in Linux (1/3)

- Process descriptor: `type struct task_struct`
- Approx 1.7KB of memory
- New task $\rightarrow$ allocate new struct from cache
  - Will use existing free `struct task_struct`
- Slab can be in three possible states
  - Full: all used
  - Empty: all free
  - Partial: mix of free and used

Slab Allocator in Linux (2/3)

- Upon request, slab allocator
  1. Uses free struct in partial slab.
  2. If none, takes one from empty slab.
  3. If no empty slab, create new empty.

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- Kernel 2.2 had SLAB.
- Recent distribution added two more allocators:
  - SLOB (Simple List of Blocks): for systems with limited memory, maintains 3 list objects for small, medium, large objects
  - SLUB is performance-optimized SLAB, removes per-CPU queues, metadata stored in page structure, from kernel 2.6.24

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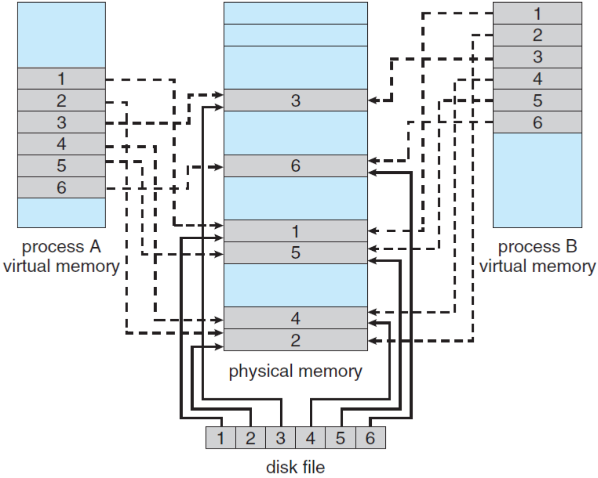
- A file is initially read using demand paging.
    - A page-sized portion of the file is read from the file system into a physical page.
    - Subsequent reads/writes to/from the file are treated as ordinary memory accesses.

Memory-Mapped Files (2/3)



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- Also allows several processes to map the same file allowing the pages in memory to be shared.
- When does written data make it to disk?
  - Periodically and/or at file `close()` time.

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- Ranges of memory addresses are mapped to the device registers.
- Reads and writes to these memory addresses cause the data to be transferred to and from the device registers.
  - Called, I/O port

Other Considerations

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- Prepage all or some of the pages a process will need, before they are referenced.
- If prepaged pages are unused, I/O and memory was wasted.
- Assume s pages are prepaged and a fraction $0 \leq \alpha \leq 1$ of the pages are used.
  - Cost of $s \times \alpha$ $>$ or $<$ than the cost of prepaging $s \times (1 - \alpha)$ unnecessary pages?
  - If α close to 0: prepaging loses; if α close to 1, prepaging wins

Page Size

- Page size selection must take into consideration:
  - Fragmentation
  - Page table size
  - Resolution
  - I/O overhead
  - Number of page faults
  - Locality
  - TLB size and effectiveness
- Always power of 2

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- Increase the page size
  - This may lead to an increase in fragmentation

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- TLB reach = (TLB Size) × (Page Size)
- Ideally, the working set of each process is stored in the TLB
  - Otherwise there is a high degree of page faults.
- Increase the page size
  - This may lead to an increase in fragmentation
- Provide multiple page sizes
  - This allows applications that require larger page sizes the opportunity to use them without an increase in fragmentation

Program Structure

- `int[128,128] data`: each row is stored in one page
- Program 1

```
for (j = 0; j <128; j++)
  for (i = 0; i < 128; i++)
    data[i, j] = 0;
```

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$128 \times 128 = 16,384$ page faults

Program Structure

- `int[128,128] data`: each row is stored in one page
- Program 1

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for (j = 0; j <128; j++)
  for (i = 0; i < 128; i++)
    data[i, j] = 0;
```

$128 \times 128 = 16,384$ page faults

- Program 2

```
for (i = 0; i <128; j++)
  for (j = 0; j < 128; i++)
    data[i, j] = 0;
```

Program Structure

- `int[128,128] data`: each row is stored in one page
- Program 1

```
for (j = 0; j <128; j++)
  for (i = 0; i < 128; i++)
    data[i, j] = 0;
```

$128 \times 128 = 16,384$ page faults

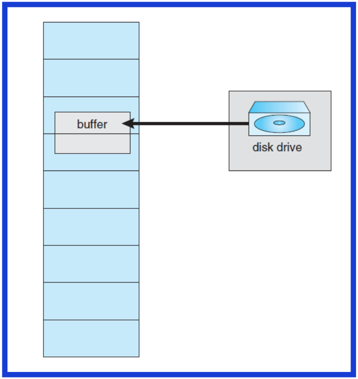
- Program 2

```
for (i = 0; i <128; j++)
  for (j = 0; j < 128; i++)
    data[i, j] = 0;
```

128 page faults

I/O Interlock

- I/O interlock: pages must sometimes be locked into memory.
- Consider I/O: pages that are used for copying a file from a device must be locked from being selected for eviction by a page replacement algorithm.



Summary

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- Frame allocation: fixed and priority allocations
- Global and local allocation
- Thrashing: total demand frames > total num. of frames
- Prevent trashing: working set model and page fault frequency
- Allocating kernel memory: buddy system and slab allocation
- Memory-mapped files and I/O

Questions?

Acknowledgements

Some slides were derived from Avi Silberschatz slides.