CSE 4733/6733 - Operating System 1

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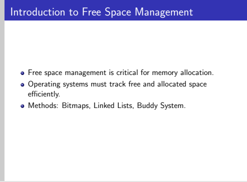
Introduction to Free Space Management

- Free space management is critical for memory allocation.
- Operating systems must track free and allocated space efficiently.
- Methods: Bitmaps, Linked Lists, Buddy System.



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1. Before diving into paging and address translation, let's understand how the OS manages free space in memory.
2. Think of free space like available parking spots; the OS must track which spots are empty and assign them efficiently.

Key Reasons Why Free Space Management Matters

- Prevents Wasted Memory
- Optimizes Performance
- Supports Dynamic Memory Needs
- Ensures Stability & Predictability

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1. **Prevents Wasted Memory**: Without effective free space tracking, allocated memory can become scattered, leading to fragmentation. Poor management results in unusable memory blocks, even when there is "free" space.
2. **Optimizes Performance**: Fast allocation and deallocation ensure low latency for memory requests. Reducing fragmentation allows the system to minimize paging overhead (this connects to your TLB discussion).
3. **Supports Dynamic Memory Needs**: OS memory demands change dynamically. Efficient tracking enables smooth scaling for multi-process workloads. Poor memory tracking leads to high page table overhead, increasing TLB misses.

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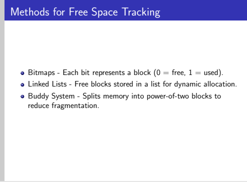
1. **Ensures Stability and Predictability**: Without structured memory tracking, memory allocations may fail unpredictably. OS crashes and instability can occur when free memory isn't managed properly.

Methods for Free Space Tracking

- Bitmaps - Each bit represents a block (0 = free, 1 = used).
- Linked Lists - Free blocks stored in a list for dynamic allocation.
- Buddy System - Splits memory into power-of-two blocks to reduce fragmentation.



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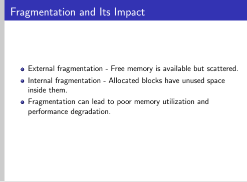
1. - "Bitmaps are simple but require scanning to find free blocks." - "Linked lists allow quick merges but add pointer overhead." - "The Buddy System helps balance efficiency and performance."

Fragmentation and Its Impact

- External fragmentation - Free memory is available but scattered.
- Internal fragmentation - Allocated blocks have unused space inside them.
- Fragmentation can lead to poor memory utilization and performance degradation.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- Internal fragmentation - Allocated blocks have unused space inside them.
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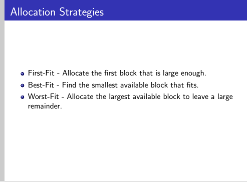
1. - "Imagine a bookshelf with empty spaces between books - that's fragmentation." - "External fragmentation wastes large portions of memory."

Allocation Strategies

- First-Fit - Allocate the first block that is large enough.
- Best-Fit - Find the smallest available block that fits.
- Worst-Fit - Allocate the largest available block to leave a large remainder.


Allocation Strategies

- First-Fit - Allocate the first block that is large enough.
- Best-Fit - Find the smallest available block that fits.
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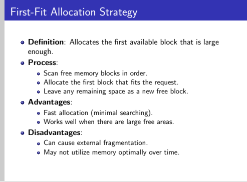
1. - "First-Fit is fast but can cause fragmentation." - "Best-Fit minimizes leftover space but increases search time." - "Worst-Fit can lead to larger continuous free blocks."

First-Fit Allocation Strategy

- **Definition**: Allocates the first available block that is large enough.
- **Process**:
  - Scan free memory blocks in order.
  - Allocate the first block that fits the request.
  - Leave any remaining space as a new free block.
- **Advantages**:
  - Fast allocation (minimal searching).
  - Works well when there are large free areas.
- **Disadvantages**:
  - Can cause external fragmentation.
  - May not utilize memory optimally over time.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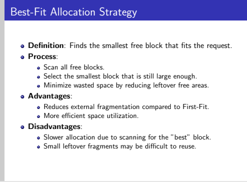
1. First-Fit is efficient when memory is mostly free but can degrade performance due to fragmentation.

Best-Fit Allocation Strategy

- **Definition**: Finds the smallest free block that fits the request.
- **Process**:
  - Scan all free blocks.
  - Select the smallest block that is still large enough.
  - Minimize wasted space by reducing leftover free areas.
- **Advantages**:
  - Reduces external fragmentation compared to First-Fit.
  - More efficient space utilization.
- **Disadvantages**:
  - Slower allocation due to scanning for the "best" block.
  - Small leftover fragments may be difficult to reuse.



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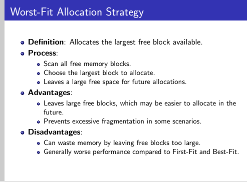
- **Disadvantages**:
  - Slower allocation due to scanning for the "best" block.
  - Small leftover fragments may be difficult to reuse.

1. Best-Fit is good for maximizing memory usage but can lead to tiny, unusable fragments.

Worst-Fit Allocation Strategy

- **Definition**: Allocates the largest free block available.
- **Process**:
  - Scan all free memory blocks.
  - Choose the largest block to allocate.
  - Leaves a large free space for future allocations.
- **Advantages**:
  - Leaves large free blocks, which may be easier to allocate in the future.
  - Prevents excessive fragmentation in some scenarios.
- **Disadvantages**:
  - Can waste memory by leaving free blocks too large.
  - Generally worse performance compared to First-Fit and Best-Fit.



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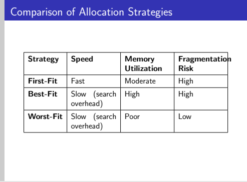
  - Generally worse performance compared to First-Fit and Best-Fit.

1. Worst-Fit aims to maintain large free areas but often results in poor memory utilization.

Comparison of Allocation Strategies

Strategy	**Speed**	**Memory Utilization**	**Fragmentation Risk**
First-Fit	Fast	Moderate	High
Best-Fit	Slow (search overhead)	High	High
Worst-Fit	Slow (search overhead)	Poor	Low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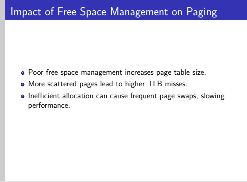
1. No single strategy is perfect—trade-offs depend on system workload and memory usage patterns.
2. Best-Fit is great for maximizing memory usage but may lead to fragmentation.
3. First-Fit is efficient when memory is mostly free, but fragmentation becomes a concern over time.
4. Worst-Fit is rarely used in practice due to inefficient memory utilization.

Impact of Free Space Management on Paging

- Poor free space management increases page table size.
- More scattered pages lead to higher TLB misses.
- Inefficient allocation can cause frequent page swaps, slowing performance.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- More scattered pages lead to higher TLB misses.
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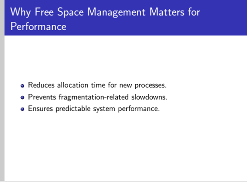
1. - "Poor free space management means more fragmented pages, which increases lookup times." - "Efficient allocation reduces page table overhead."

Why Free Space Management Matters for Performance

- Reduces allocation time for new processes.
- Prevents fragmentation-related slowdowns.
- Ensures predictable system performance.



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- Reduces allocation time for new processes.
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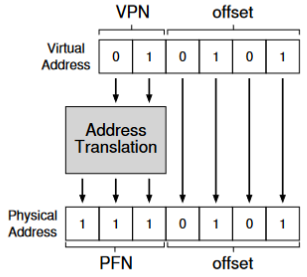
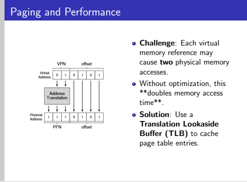
1. - "Without efficient free space tracking, memory allocation can slow down over time." - "Well-managed memory keeps the system responsive and efficient."

Paging and Performance



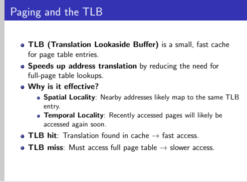
- **Challenge**: Each virtual memory reference may cause **two** physical memory accesses.
- Without optimization, this **doubles memory access time**.
- **Solution**: Use a **Translation Lookaside Buffer (TLB)** to cache page table entries.



1. **Why does this matter?** Every memory access requires looking up a page table entry, which adds overhead.
2. **Real-world analogy:** Imagine checking a physical map every time you drive to a location vs. having a GPS preloaded with frequent routes.
3. **Key takeaway:** Without caching, paging becomes expensive. This is where the TLB comes in.

Paging and the TLB

- **TLB (Translation Lookaside Buffer)** is a small, fast cache for page table entries.
- **Speeds up address translation** by reducing the need for full-page table lookups.
- **Why is it effective?**
  - **Spatial Locality**: Nearby addresses likely map to the same TLB entry.
  - **Temporal Locality**: Recently accessed pages will likely be accessed again soon.
- **TLB hit**: Translation found in cache → fast access.
- **TLB miss**: Must access full page table → slower access.



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- **TLB hit**: Translation found in cache → fast access.
- **TLB miss**: Must access full page table → slower access.

1. **Why is this important?** Without a TLB, every virtual memory reference requires a full-page table lookup, which slows performance.
2. **TLB hit rate:** A high hit rate means the TLB is doing its job well. A low hit rate means more page table lookups, causing slowdowns.
3. **Analogy:** Think of a **TLB like a speed dial** on your phone. If a contact is in speed dial (cache), you call them instantly (fast lookup). Otherwise, you must go through the contact list (slow lookup).

Paging and the TLB

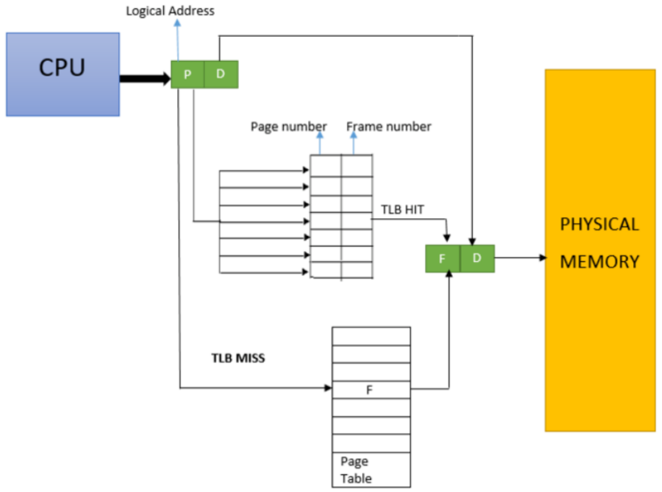
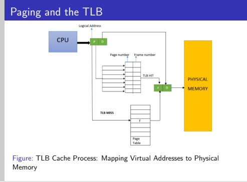


Figure: TLB Cache Process: Mapping Virtual Addresses to Physical Memory



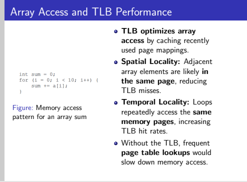
1. **What is happening in the diagram?** The CPU generates a logical address with a page number and offset. If the TLB contains the mapping (hit), it directly provides the frame number. If not, the system consults the full page table (miss), causing a delay.
2. **Real-world analogy:** Think of the TLB like a frequent contacts list in a phone. If a number is saved, you dial it instantly. If not, you must search manually, taking extra time.
3. **Key takeaway:** TLBs are critical for high-performance memory access and reducing paging overhead.

Array Access and TLB Performance

```
int sum = 0;
for (i = 0; i < 10; i++) {
    sum += a[i];
}
```

Figure: Memory access pattern for an array sum

- **TLB optimizes array access** by caching recently used page mappings.
- **Spatial Locality:** Adjacent array elements are likely **in the same page**, reducing TLB misses.
- **Temporal Locality:** Loops repeatedly access the **same memory pages**, increasing TLB hit rates.
- Without the TLB, frequent **page table lookups** would slow down memory access.



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- Without the TLB, frequent **page table lookups** would slow down memory access.

1. **How does TLB help?** Instead of looking up every array index in the page table, the TLB caches recent translations, making repeated accesses much faster.
2. **Analogy:** Think of scanning a bookshelf. If the books are in order (**spatial locality**), you find them quickly. If you keep reading the same book (**temporal locality**), there's no need to search again.
3. **Key takeaway:** The TLB greatly enhances performance by reducing the need for page table lookups, especially in **looped array operations**.

Array Example: Virtual Page Numbers (VPN) and TLB Performance

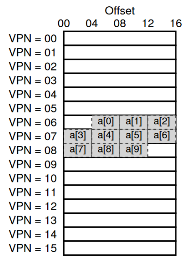
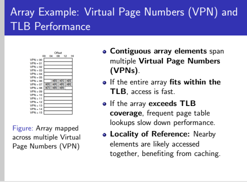


Figure: Array mapped across multiple Virtual Page Numbers (VPN)

- **Contiguous array elements** span multiple **Virtual Page Numbers (VPNs)**.
- If the entire array **fits within the TLB**, access is fast.
- If the array **exceeds TLB coverage**, frequent page table lookups slow down performance.
- **Locality of Reference:** Nearby elements are likely accessed together, benefiting from caching.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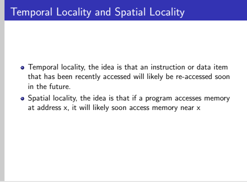
- **Locality of Reference:** Nearby elements are likely accessed together, benefiting from caching.

1. **What is happening here?** The array is spread across multiple virtual pages (VPNs). The TLB caches page table entries to speed up access.
2. **Why does this matter?** If the array is too large for the TLB, each new page access requires a full page table lookup, increasing memory access time.
3. **Analogy:** Imagine reading a large book where each chapter is on a different floor of a library. If you can store the whole book on your desk (TLB hit), reading is fast. If not, you have to retrieve pages frequently (TLB miss).

Temporal Locality and Spatial Locality

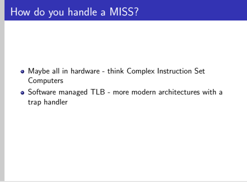
- Temporal locality, the idea is that an instruction or data item that has been recently accessed will likely be re-accessed soon in the future.
- Spatial locality, the idea is that if a program accesses memory at address x, it will likely soon access memory near x



1. TLB Reality Check:
   - Cache always has a MISS and HIT possibility - see some cache traces in the book
   - Scale of performance between CACHE and standard memory access is dramatic, a few CPU cycles vs. nanoseconds
   - Reality checks on performance are the costs and the physics involved

How do you handle a MISS?

- Maybe all in hardware - think Complex Instruction Set Computers
- Software managed TLB - more modern architectures with a trap handler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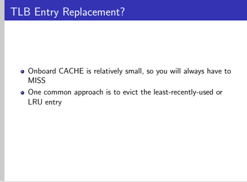
1. TLB Reality Check:
   - Startup, nothing loaded and have to get popular VPN to PFN loaded over time
   - Flush on a context switch?
   - How do we minimize the miss rate (or increase the hit rate)

TLB Entry Replacement?

- Onboard CACHE is relatively small, so you will always have to MISS
- One common approach is to evict the least-recently-used or LRU entry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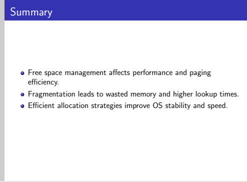
1. TLB Replacement:
   - Flush on every context switch, or have an address space identifier (ASID)
   - Support of ASID says we can have TLB that supports multiple processes at the same time
   - LRU means we have to keep track of the usage and timestamp entries
   - LRU helps with the locality of reference; old stuff is dropped for the recent access

Summary

- Free space management affects performance and paging efficiency.
- Fragmentation leads to wasted memory and higher lookup times.
- Efficient allocation strategies improve OS stability and speed.


Summary

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- Fragmentation leads to wasted memory and higher lookup times.
- Efficient allocation strategies improve OS stability and speed.

1. - "Understanding free space management is key to optimizing memory use." - "Next, we'll look at advanced paging techniques and memory hierarchies."

References I

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└─References