EXTERNAL MEMORY COMPUTING

- hierarchical memory management
- B-trees
- external sorting
The Memory Hierarchy

- Many problems that modern computers are given to solve (analyzing scientific data, running Win95, etc.) require large amounts of storage.

- In an ideal world, all the necessary information could be stored on chip in the processor’s registers, but that would be hideously expensive.

- Instead, computers use a memory hierarchy where there is a tradeoff between speed and volume.

- The hierarchy consists of four layers:
  - Registers
  - Cache memory
  - Internal memory (RAM)
  - External memory (Disk)
The Memory Hierarchy (contd.)

- The hierarchy (for a typical workstation):

<table>
<thead>
<tr>
<th>Access time (CPU cycles)</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Registers: 1 cycle</td>
<td>(\sim 2^{10}) bytes</td>
</tr>
<tr>
<td>Cache: 5 cycles</td>
<td>(\sim 2^{20}) bytes</td>
</tr>
<tr>
<td>Internal: 50 cycles</td>
<td>(\sim 2^{26}) bytes</td>
</tr>
<tr>
<td>External: 2,000,000 cycles</td>
<td>(\sim 2^{32}) bytes</td>
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</tbody>
</table>
Caching and Blocking

• Since the performance loss is so great when external memory needs to be accessed, several techniques have been developed to avoid this bottleneck.

• These are based on one of two assumptions about the data:
  - Temporal Locality: If data is used once, it will probably be needed again soon after.
  - Spatial Locality: If data is used once, the data next to it will probably be needed soon after.

• **Caching** uses virtual memory which is based on Temporal Locality.
  - An address space is provided that is as large as the secondary storage space.
  - When data is requested from secondary storage, it is transferred to primary storage (cached).

• **Blocking** is based on Spatial Locality.
  - When data is requested from secondary storage, a large contiguous block of data is transferred into primary storage.
    (a block of data is paged).
Block Replacement Policies

- We assume we have a **fully associative cache**, that is, a block from external memory can be placed in any slot of the cache.

- The CPU determines if the virtual memory location accessed is in the cache, and if so where.

- If it is not in the cache the block of external memory, containing the location is transferred into the cache.

- If there are no slots free in the cache, then we must determine which block should be evicted.

- Common policies to determine the block to evict:
  - Random
  - First-In, First-out (FIFO)
  - Least Frequently used (LFU)
  - Least Recently used (LRU)

- **Random** is easy to implement and takes $O(1)$ time
Block Replacement Policies (cont)

- **FIFO** is also easy to implement, it uses temporal locality and takes $O(1)$ time.

  FIFO policy:

  New block: 8:00am 7:48am 9:05am 7:10am 7:30am 10:10am 8:45am 7:48am
  Old block (present longest): insertion time

- **LFU** requires more overhead but can still be implemented in $O(1)$ time using a special type of priority queue. But it penalizes recently added blocks.

  LRU policy:

  New block: 7:25am 8:12am 9:22am 6:50am 8:20am 10:02am 9:50am 8:12am
  Old block (least recently used): last access time

- **LRU** is the most effective policy in practice. It can be implemented in $O(1)$ time with a special type of priority queue.
The Marker Policy

- mark bit associated with every block in the cache
- if a block in the cache is accessed, it is marked
- if all the blocks become marked, they get all unmarked
- evict a random unmarked block

Marker policy:

- this policy is a good approximation of LRU, but is simpler to implement
External Searching

• Let’s look at the problem of implementing a dictionary of a large collection of items that do not fit in primary memory.

• In maintaining a dictionary in external memory we want to minimize the number of times we transfer a block between secondary and primary memory, known as a disk transfer, during queries and updates.

• The list-based sequence implementation of a dictionary requires $O(n)$ transfers per query or update.

• The array-based sequence implementation of a dictionary requires $O(n/B)$ transfers per query or update, where $B$ is the size of a block.

• In a binary search tree implementation of a dictionary, in the worst case each node accessed will be in a different block. Thus it requires at least $\log n$ transfers per query or update.

• But we can do better ...
(a, b) Trees

- An (a,b) tree is a tree such that:
  - a and b are integers such that $2 \leq a \leq (b+1)/2$
  - each internal node has at least a children and at most b children
  - all external nodes have the same depth

- Insertion and deletion are similar to insertion and deletion in (2, 4) trees.

- Properties:
  - the height is $O(\log_a n)$, that is, $O(\log n / \log a)$
  - processing a node takes $t(b)$ time

- A search, insertion, or deletion takes time:
  \[
  O\left(\frac{t(b)}{\log a} \log n\right)
  \]

  and accesses
  \[
  O\left(\frac{\log n}{\log a}\right)
  \]

  nodes ($O(1)$ nodes for each level of the tree).
Example
B-Trees

• To minimize disk access we must select values for a and b such that each tree node occupies a single disk block.

• Let B be the size of a block

• A B-tree of order d is an (a,b) tree with a = d/2 and b=d.

• We choose d such that a node fits into a single disk block. This implies a, b, and d are Θ(B).

• Each search or update requires accessing O(log n / log a) nodes.

• Thus, an B-tree requires O(log n / log B) disk transfers for any update or search operation.