CS4102 Algorithms
Spring 2019

Warm up

Why is an algorithm's space complexity (how much memory it uses) important?

Why might a memory-intensive algorithm be a "bad" one?

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Why lots of memory is "bad"

- limited by size of memory
- different speeds / sizes of memory
- memory is SLOW / CPU is fast
- cache misses
- fast memory = $$
- memory ≤ time

more memory ⇒ slower memory

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Today's Keywords

- Greedy Algorithms
- Choice Function
- Cache Replacement
- Hardware & Algorithms

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CLRS Readings

- Chapter 16

Homeworks

- HW6 Due Friday April 5 @11pm
  - Written (use latex)
  - DP and Greedy

Goal: Shortest Prefix-Free Encoding

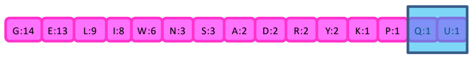
- Input: A set of character frequencies $\{f_c\}$
- Output: A prefix-free code T which minimizes

$$B(T, \{f_c\}) = \sum_{character\ c} \ell_c f_c$$

Huffman Coding!!

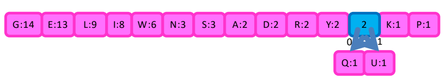
Huffman Algorithm

- Choose the least frequent pair, combine into a subtree



Huffman Algorithm

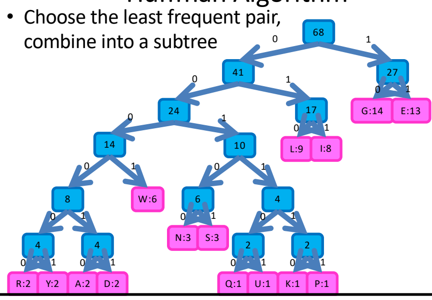
- Choose the least frequent pair, combine into a subtree



Subproblem of size $n-1$!

Huffman Algorithm

- Choose the least frequent pair, combine into a subtree



REVIEW: Showing Huffman is Optimal

- Overview:
  - Show that there is an optimal tree in which the least frequent characters are siblings — Greedy Choice Property
    - Exchange argument
  - Show that making them siblings and solving the new smaller sub-problem results in an optimal solution — Optimal Substructure works
    - Proof by contradiction

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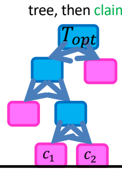
Huffman Exchange Argument

- Claim: if c_1, c_2 are the least-frequent characters, then there is an optimal prefix-free code s.t. c_1, c_2 are siblings
  - i.e. codes for c_1, c_2 are the same length and differ only by their last bit

Case 1: Consider some optimal tree T_{opt}. If c_1, c_2 are siblings in this tree, then claim holds



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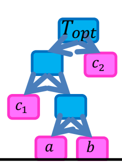
Huffman Exchange Argument

- Claim: if c_1, c_2 are the least-frequent characters, then there is an optimal prefix-free code s.t. c_1, c_2 are siblings
  - i.e. codes for c_1, c_2 are the same length and differ only by their last bit

Case 2: Consider some optimal tree T_{opt}, in which c_1, c_2 are not siblings



Let a, b be the two characters of lowest depth that are siblings
(Why must they exist?)

Idea: show that swapping c_1 with a does not increase cost of the tree.
Similar for c_2 and b
Assume: $f_{c1} \leq f_a$ and $f_{c2} \leq f_b$

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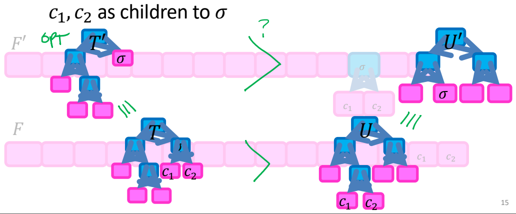
Optimal Substructure

- Claim: An optimal solution for F involves finding an optimal solution for F', then adding c_1, c_2 as children to σ

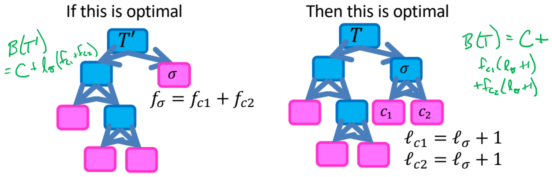


Optimal Substructure

- Claim: An optimal solution for F involves finding an optimal solution for F', then adding c_1, c_2 as children to σ

If this is optimal

Then this is optimal



$B(T') = C + \ell_\sigma(f_{c1} + f_{c2})$

$f_\sigma = f_{c1} + f_{c2}$

$B(T) = C + f_{c1}(\ell_\sigma + 1) + f_{c2}(\ell_\sigma + 1)$

$\ell_{c1} = \ell_\sigma + 1$
$\ell_{c2} = \ell_\sigma + 1$

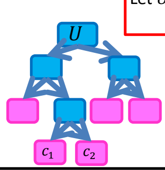
$B(T') = B(T) - f_{c1} - f_{c2}$

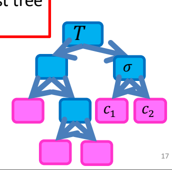
Optimal Substructure

- Claim: An optimal solution for F involves finding an optimal solution for F', then adding c_1, c_2 as children to σ

Toward contradiction

Suppose T is not optimal
Let U be a lower-cost tree
$B(U) < B(T)$





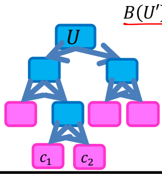
Optimal Substructure

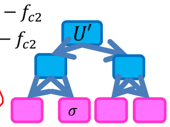
- Claim: An optimal solution for F involves finding an optimal solution for F', then adding c_1, c_2 as children to σ

$B(U) < B(T)$

$$B(U') = \boxed{B(U)} - f_{c1} - f_{c2}$$
$$< \boxed{B(T)} - f_{c1} - f_{c2}$$
$$= B(T')$$

$B(U') < B(T')$





Contradicts optimality of T', so T is optimal!

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Caching Problem

- Why is using too much memory a bad thing?

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Von Neumann Bottleneck

- Named for John von Neumann
- Inventor of modern computer architecture
- Other notable influences include:
  - Mathematics
  - Physics
  - Economics
  - Computer Science

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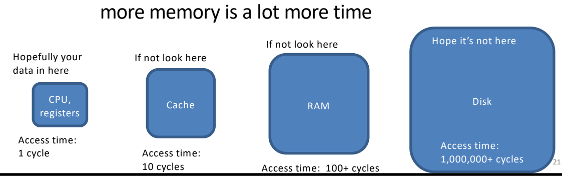
Von Neumann Bottleneck

- Reading from memory is VERY slow
- Big memory = slow memory
- Solution: hierarchical memory
- Takeaway for Algorithms: Memory is time, more memory is a lot more time



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Caching Problem

- Cache misses are very expensive
- When we load something new into cache, we must eliminate something already there
- We want the best cache "schedule" to minimize the number of misses

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Caching Problem Definition

- Input:
  - k = size of the cache
  - $M = [m_1, m_2, \ldots m_n]$ = memory access pattern
- Output:
  - "schedule" for the cache (list of items in the cache at each time) which minimizes cache fetches

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Example

A B C D A D E A D B A E C E A

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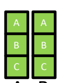
Example



A B C D A D E A D B A E C E A

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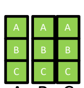
Example



A B C D A D E A D B A E C E A

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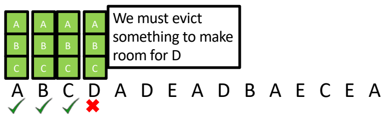
Example



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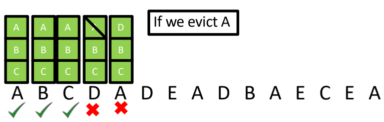
Example



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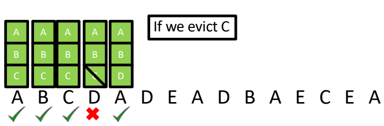
Example



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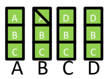
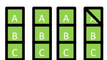
Our Problem vs Reality

- Assuming we know the entire access pattern
- Cache is Fully Associative
- Counting # of fetches (not necessarily misses)
- "Reduced" Schedule: Address only loaded on the cycle it's required
  - Reduced == Unreduced (by number of fetches)



Unreduced

A B C D A D E A D B A E C E A



Reduced

Leaving A in longer does not save fetches

A B C D A D E A D B A E C E A

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Greedy Algorithms

- Require Optimal Substructure
  - Solution to larger problem contains the solution to a smaller one
  - Only one subproblem to consider!
- Idea:
  1. Identify a greedy choice property
     - How to make a choice guaranteed to be included in some optimal solution
  2. Repeatedly apply the choice property until no subproblems remain

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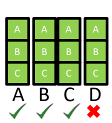
Greedy choice property

- Belady evict rule:
  - Evict the item accessed farthest in the future



Evict C

A B C D A D E A D B A E C E A

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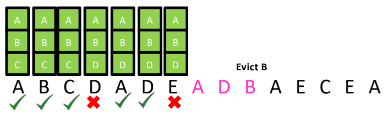
Greedy choice property

- Belady evict rule:
  – Evict the item accessed farthest in the future



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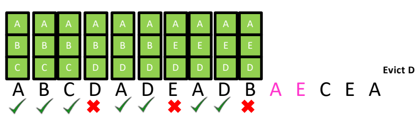

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Greedy choice property

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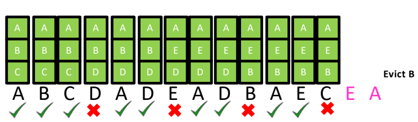

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Greedy choice property

- Belady evict rule:
  - Evict the item accessed farthest in the future

A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
B	B	B	B	B	B	E	E	E	E	E	E	E	E	E
C	C	C	D	D	D	D	D	D	B	B	B	C	C	C
A	B	C	D	A	D	E	A	D	B	A	E	C	E	A
✓	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓

4 Cache Misses

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Greedy Algorithms

- Require Optimal Substructure
  - Solution to larger problem contains the solution to a smaller one
  - Only one subproblem to consider!
- Idea:
  1. Identify a greedy choice property
     - How to make a choice guaranteed to be included in some optimal solution
  2. Repeatedly apply the choice property until no subproblems remain

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Caching Greedy Algorithm

Initialize $cache$= first k accesses $O(k)$
For each $m_i \in M$: n times
    if $m_i \in cache$: $O(k)$
        print $cache$ $O(k)$
    else:
        $m =$ furthest-in-future from cache $O(kn)$
        evict m, load m_i $O(1)$
        print $cache$ $O(k)$

$O(kn^2)$

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Exchange argument

- Shows correctness of a greedy algorithm
- Idea:
  - Show exchanging an item from an arbitrary optimal solution with your greedy choice makes the new solution no worse
  - How to show my sandwich is at least as good as yours:
    - Show: "I can remove any item from your sandwich, and it would be no worse by replacing it with the same item from my sandwich"

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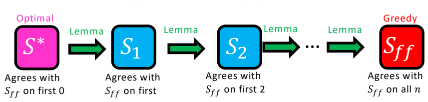
Belady Exchange Lemma

Let S_{ff} be the schedule chosen by our greedy algorithm

Let S_i be a schedule which agrees with S_{ff} for the first i memory accesses.

We will show: there is a schedule S_{i+1} which agrees with S_{ff} for the first $i+1$ memory accesses, and has no more misses than S_i

(i.e. $misses(S_{i+1}) \leq misses(S_i)$)



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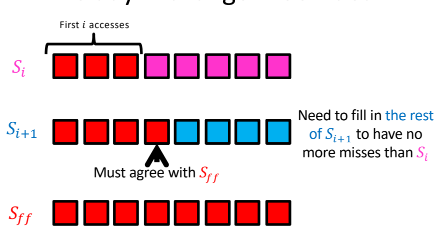
Belady Exchange Proof Idea



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Proof of Lemma

Goal: find S_{i+1} s.t. $misses(S_{i+1}) \leq misses(S_i)$

Since S_i agrees with S_{ff} for the first i accesses, the state of the cache at access $i+1$ will be the same

[S_i Cache after i | e | f] $=$ [S_{ff} Cache after i | e | f]

Consider access $m_{i+1} = d$

Case 1: if d is in the cache, then neither S_i nor S_{ff} evict from the cache, use the same cache for S_{i+1}

[S_{i+1} Cache after i | e | f]

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Proof of Lemma

Goal: find S_{i+1} s.t. $misses(S_{i+1}) \leq misses(S_i)$

Since S_i agrees with S_{ff} for the first i accesses, the state of the cache at access $i+1$ will be the same

[S_i Cache after i | e | f] $=$ [S_{ff} Cache after i | e | f]

Consider access $m_{i+1} = d$

Case 2: if d isn't in the cache, and both S_i and S_{ff} evict f from the cache, evict f for d in S_{i+1}

[S_{i+1} Cache after i | e | d]

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Proof of Lemma

Goal: find S_{i+1} s.t. $misses(S_{i+1}) \leq misses(S_i)$

Since S_i agrees with S_{ff} for the first i accesses, the state of the cache at access $i+1$ will be the same

[S_i Cache after i | e | f] $=$ [S_{ff} Cache after i | e | f]

Consider access $m_{i+1} = d$

Case 3: if d isn't in the cache, S_i evicts e and S_{ff} evicts f from the cache

[S_i Cache after $i+1$ | d | f] $\neq$ [S_{ff} Cache after $i+1$ | e | d]

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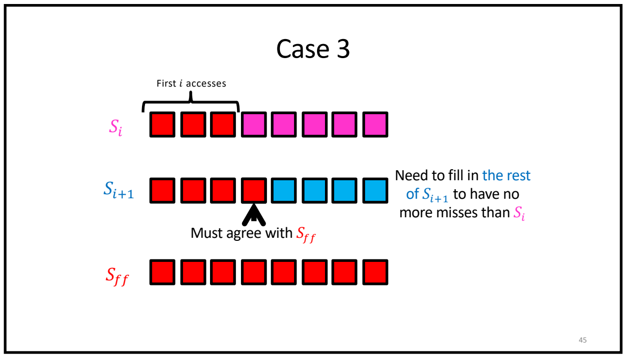
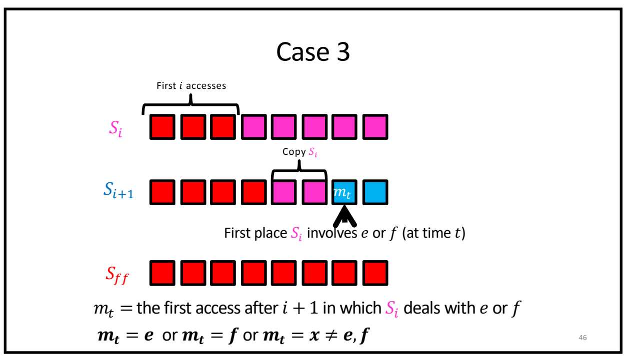
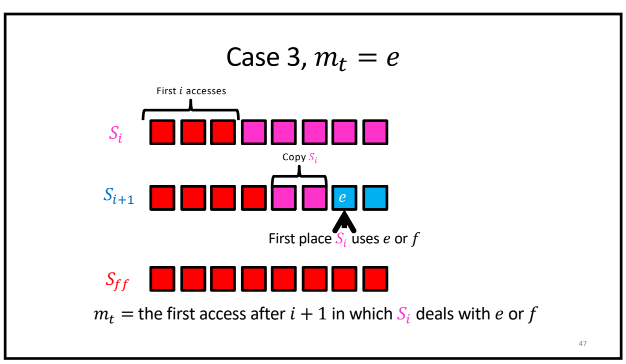

Case 3
First i accesses
S_i
S_{i+1}
Need to fill in the rest of S_{i+1} to have no more misses than S_i
Must agree with S_{ff}
S_{ff}
45


Case 3
First i accesses
S_i
Copy S_i
S_{i+1}
m_t
First place S_i involves e or f (at time t)
S_{ff}
m_t = the first access after $i + 1$ in which S_i deals with e or f
$\boldsymbol{m_t = e}$ or $\boldsymbol{m_t = f}$ or $\boldsymbol{m_t = x \neq e, f}$
46


Case 3, $m_t = e$
First i accesses
S_i
Copy S_i
S_{i+1}
e
First place S_i uses e or f
S_{ff}
m_t = the first access after $i + 1$ in which S_i deals with e or f
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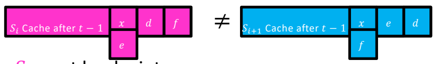
Case 3, $m_t = e$

Goal: find S_{i+1} s.t. $misses(S_{i+1}) \leq misses(S_i)$



S_i must load e into the cache, assume it evicts x

S_{i+1} will load f into the cache, evicting x

The caches now match!

S_{i+1} behaved exactly the same as S_i between i and t, and has the same cache after t, therefore $misses(S_{i+1}) = misses(S_i)$

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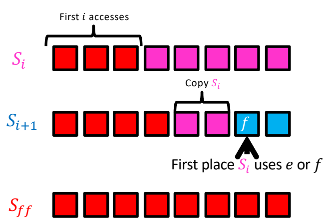
Case 3, $m_t = f$



m_t = the first access after $i+1$ in which S_i deals with e or f

$\boldsymbol{m_t = e}$ or $\boldsymbol{m_t = f}$ or $\boldsymbol{m_t = x \neq e, f}$

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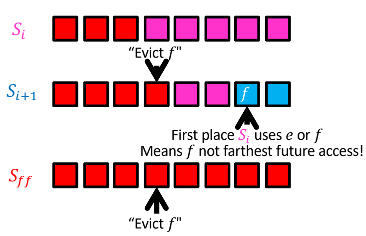
Case 3, $m_t = f$

Cannot Happen!



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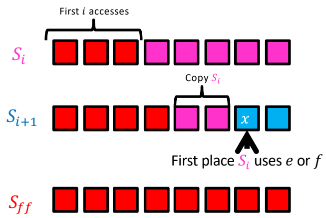
Case 3, $m_t = x \neq e, f$



$m_t =$ the first access after $i+1$ in which S_i deals with e or f

$m_t = e$ or $m_t = f$ or $m_t = x \neq e, f$

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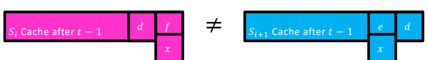
Case 3, $m_t = x \neq e, f$

Goal: find S_{i+1} s.t. $misses(S_{i+1}) \leq misses(S_i)$



S_i loads x into the cache, it must be evicting f

S_{i+1} will load x into the cache, evicting e

The caches now match!

S_{i+1} behaved exactly the same as S_i between i and t, and has the same cache after t, therefore $misses(S_{i+1}) = misses(S_i)$

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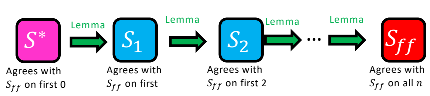
Use Lemma to show Optimality



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