CSE 326: Data Structures

Binomial Queues

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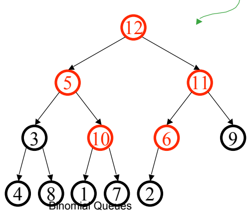
Administration

- Released today: Project 2, phase B
- Due today: Homework 1
- Released today: Homework 2
- I have office hours tomorrow

BuildHeap: Floyd's Method

12	5	11	3	10	6	9	4	8	1	7	2

Add elements arbitrarily to form a complete tree.
Pretend it's a heap and fix the heap-order property!

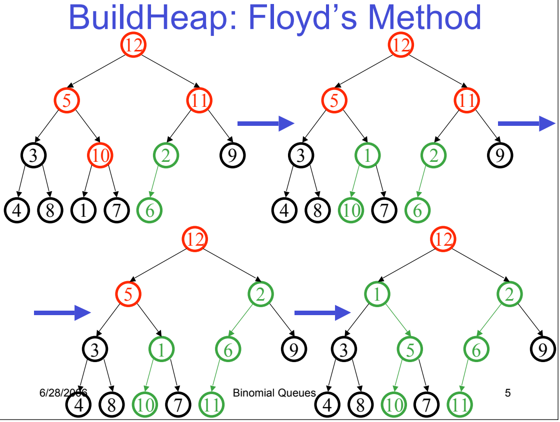


Buildheap pseudocode

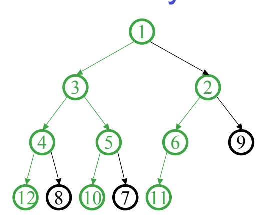
```
private void buildHeap() {
  for ( int i = currentSize/2; i > 0; i-- )
     percolateDown( i );
}
```

runtime:

BuildHeap: Floyd's Method



Finally…

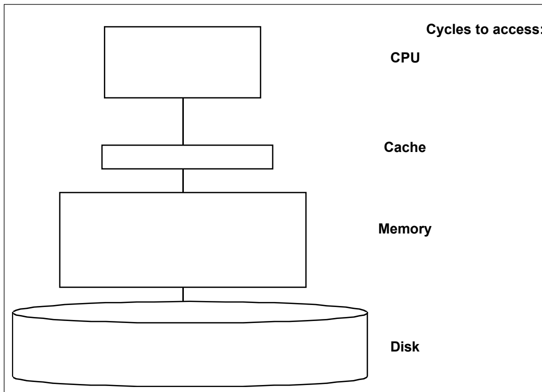


runtime:

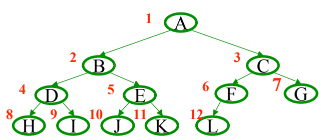
Facts about Heaps

Observations:
- finding a child/parent index is a multiply/divide by two
- operations jump widely through the heap
- each percolate step looks at only two new nodes
- inserts are at least as common as deleteMins

Realities:
- division/multiplication by powers of two are equally fast
- looking at only two new pieces of data: bad for cache!
- with huge data sets, disk accesses dominate



Representing Complete Binary Trees in an Array



From node **i**:

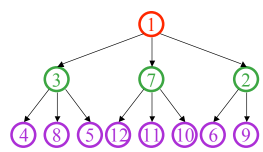
left child:
right child:
parent:

implicit (array) implementation:

	A	B	C	D	E	F	G	H	I	J	K	L	
0	1	2	3	4	5	6	7	8	9	10	11	12	13

A Solution: *d*-Heaps

- Each node has *d* children
- Still representable by array
- Good choices for *d*:
  - (choose a power of two for efficiency)
  - fit one set of children in a cache line
  - fit one set of children on a memory page/disk block



12	1	3	7	2	4	8	5	12	11	10	6	9

Operations on *d*-Heap

- Insert : runtime =
- deleteMin: runtime =

Does this help insert or deleteMin more?

One More Operation

- Merge two heaps. Ideas?

New Operation: Merge

Given two heaps, merge them into one heap

- › first attempt: insert each element of the smaller heap into the larger.
  runtime:
- › second attempt: concatenate binary heaps’ arrays and run buildHeap.
  runtime:

Merging heaps

- Binary Heap is a special purpose hot rod
  - › FindMin, DeleteMin and Insert only
  - › does not support fast merges of two heaps
- For some applications, the items arrive in prioritized clumps, rather than individually
- Is there somewhere in the heap design that we can give up a little performance so that we can gain faster merge capability?

Binomial Queues

- Binomial Queues are designed to be merged quickly with one another
- Using pointer-based design we can merge large numbers of nodes at once by simply pruning and grafting tree structures
- More overhead than Binary Heap, but the flexibility is needed for improved merging speed

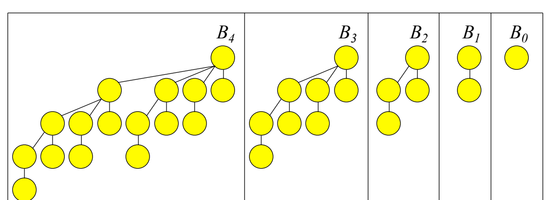
Worst Case Run Times

	Binary Heap	Binomial Queue
Insert	Θ(log N)	Θ(log N)
FindMin	Θ(1)	O(log N)
DeleteMin	Θ(log N)	Θ(log N)
Merge	Θ(N)	O(log N)

Binomial Queues

- Binomial queues give up simplicity in order to provide O(log N) merge performance
- A **binomial queue** is a collection (or *forest*) of heap-ordered trees
  - › Not just one tree, but a collection of trees
  - › each tree has a defined structure and capacity
  - › each tree has the familiar heap-order property

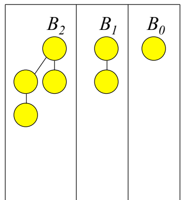
Binomial Queue with 5 Trees



depth	4	3	2	1	0
number of elements	$2^4 = 16$	$2^3 = 8$	$2^2 = 4$	$2^1 = 2$	$2^0 = 1$

Structure Property

- Each tree contains two copies of the previous tree
  - › the second copy is attached at the root of the first copy
- The number of nodes in a tree of depth *d* is exactly 2^d



depth	2	1	0
number of elements	$2^2 = 4$	$2^1 = 2$	$2^0 = 1$

Powers of 2

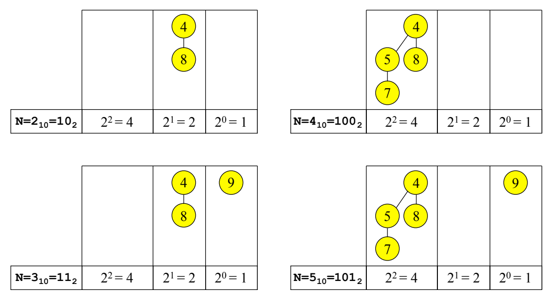
- Any number N can be represented in base 2
  - › A base 2 value identifies the powers of 2 that are to be included

$2^3 = 8_{10}$	$2^2 = 4_{10}$	$2^1 = 2_{10}$	$2^0 = 1_{10}$	Hex_{16}	$Decimal_{10}$
		1	1	3	3
	1	0	0	4	4
	1	0	1	5	5

Numbers of nodes

- Any number of entries in the binomial queue can be stored in a forest of binomial trees
- Each tree holds the number of nodes appropriate to its depth, ie 2^d nodes
- So the structure of a forest of binomial trees can be characterized with a single binary number
  - › $100_2 \rightarrow 1 \cdot 2^2 + 0 \cdot 2^1 + 0 \cdot 2^0 = 4$ nodes

Structure Examples



What is a merge?

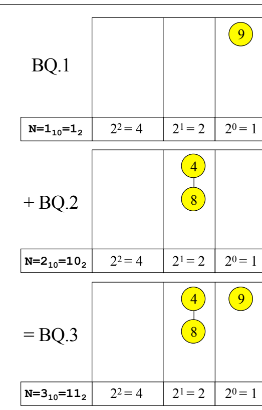
- There is a direct correlation between
  - › the number of nodes in the tree
  - › the representation of that number in base 2
  - › and the actual structure of the tree
- When we merge two queues, the number of nodes in the new queue is the *sum of* N_1+N_2
- We can use that fact to help see how fast merges can be accomplished

Example 1.

Merge BQ.1 and BQ.2

Easy Case.

There are no comparisons and there is no restructuring.

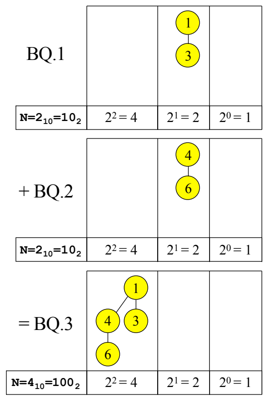


Example 2.

Merge BQ.1 and BQ.2

This is an add with a carry out.

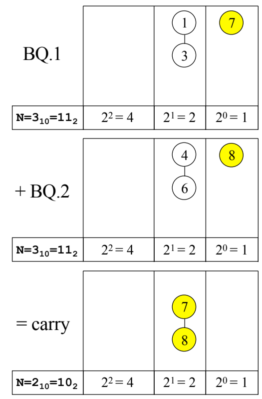
It is accomplished with one comparison and one pointer change: O(1)

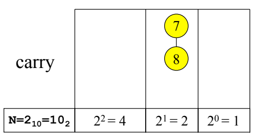


Example 3.

Merge BQ.1 and BQ.2

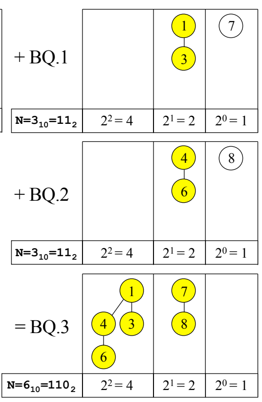
Part 1 - Form the carry.





Example 3.

Part 2 - Add the existing values and the carry.

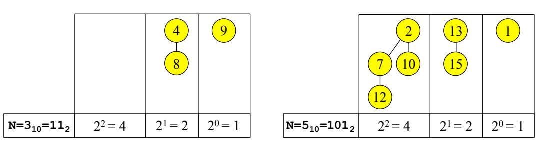


Merge Algorithm

- Just like binary addition algorithm
- Assume trees $X_0,\ldots,X_n$ and $Y_0,\ldots,Y_n$ are binomial queues
  - X_i and Y_i are of type B_i or null

```
C0 := null; //initial carry is null//
for i = 0 to n do
  combine Xi,Yi, and Ci to form Zi and new Ci+1
Zn+1 := Cn+1
```


Exercise



O(log N) time to Merge

- For N keys there are at most $\lceil \log_2 N \rceil$ trees in a binomial forest.
- Each merge operation only looks at the root of each tree.
- Total time to merge is O(log N).

Insert

- Create a single node queue B_0 with the new item and merge with existing queue
- O(log N) time

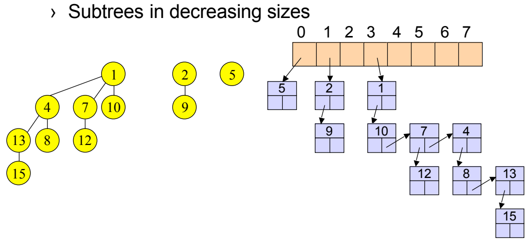
DeleteMin

1. Assume we have a binomial forest $X_0,\ldots,X_m$
2. Find tree X_k with the smallest root
3. Remove X_k from the queue
4. Remove root of X_k (return this value)
   › This yields a binomial forest $Y_0, Y_1, \ldots, Y_{k-1}$.
5. Merge this new queue with remainder of the original (from step 3)

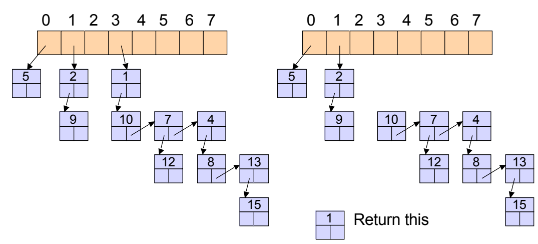
- Total time = O(log N)

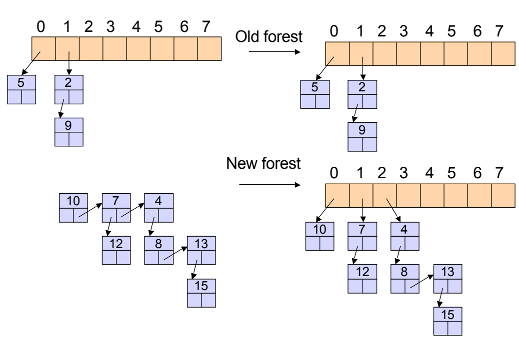
Implementation

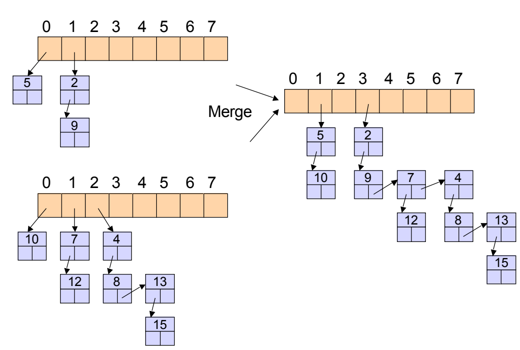
- Binomial forest as an array of multiway trees
  › FirstChild, Sibling pointers
  › Subtrees in decreasing sizes



DeleteMin Example

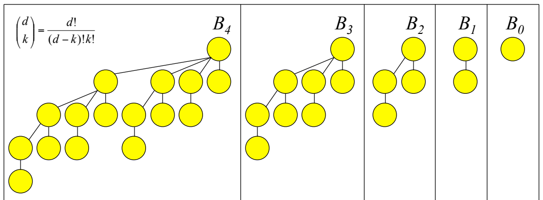






Why Binomial?

$$\binom{d}{k} = \frac{d!}{(d-k)!k!}$$



tree depth d	4	3	2	1	0
nodes at depth k	1, 4, 6, 4, 1	1, 3, 3, 1	1, 2, 1	1, 1	1

Other Priority Queues

- Leftist Heaps
  - O(log N) time for insert, deletemin, merge
- Skew Heaps
  - O(log N) amortized time for insert, deletemin, merge
- Calendar Queues
  - O(1) average time for insert and deletemin
  - Assuming insertions are “random”

Exercise Solution