**Priority queue**

- Insert $Q, x$
- Retrieve $x$ from $Q$ s.t. $x.value$ is min (or max)
- Sorted linked list:
  - $O(n)$ to insert $x$ into right place
  - $O(1)$ access-min, $O(1)$ delete-min

---

**Binary heap**

Complete – missing nodes only at the lowest level

Heap property – on any path the parent has higher priority than child

Typically: min-heaps

Priority queue
- insert $(Q, x)$
- pop $Q$

---

**Complete Binary Trees**

Array Storage

- Fill the array following a breadth-first traversal:

---

**Heap/Priority queue**

- Find min/Delete; Insert;
- Decrease key (change value of the key)
- Merge two heaps ...

---

**Binomial heaps:**

- **Performance**: All of the following operations work in $O(\log n)$ time on a binomial heap with $n$ elements:
  - Insert a new element to the heap
  - Find the element with minimum key
  - Delete the element with minimum key from the heap
  - Decrease key of a given element
  - Delete a given element from the heap
  - Merge two given heaps to one heap
  - Finding the element with minimum key can also be done in $O(1)$ by using an additional pointer to the minimum.
Binomial heaps, Fibonacci heaps, and applications

Dan Feldman

Binomial trees

Some links

- http://www.jucs.org/jucs_7_5/animator_for_teaching_purposes/Lauer_T.html
24.3.2011

Lemma 20.1

• For the binomial tree $B_k$, 
  1. there are $2^k$ nodes, 
  2. the height of the tree is $k$, 
  3. there are exactly $\binom{k}{i}$ nodes at depth $i$ for $i = 0, 1, \ldots, k$, and 
  4. the root has degree $k$, which is greater than that of any other node; moreover if the children of the root 
     are numbered from left to right by $k - 1, k - 2, \ldots, 0$, child $i$ is the root of a subtree $B_i$.

Properties of binomial trees

1) $|B_k| = 2^k$ 
2) degree(root($B_k$)) = $k$
3) depth($B_k$) = $k$

$\Rightarrow$ The degree and depth of a binomial tree with at 
most $n$ nodes is at most $\log(n)$.

Define the rank of $B_k$ to be $k$

Binomial heaps (def)

A collection of binomial trees with at most one 
of every rank.

Items at the nodes, heap ordered.

Figure 20.4 The binomial tree $B_k$ with nodes labeled in 
binary by a postorder walk.

Figure 19.3 A binomial heap $H$ with $n = 13$ nodes. (a) The heap consists of binomial trees $B_0, B_1$, and $B_2$, which have 1, 4, and 8 nodes respectively, totaling $n = 13$ nodes. Since each binomial tree is min-
heap-ordered, the key of any node is no less than the key of its parent. Also shown is the root list 
which is a linked list of roots in order of increasing degree. (b) A more detailed representation of 
binomial heap $H$. Each binomial tree is stored in the left-child, right-sibling representation, and each 
node stores its degree.

Possible rep: Doubly link roots 
and children of every node. 
Parent pointers needed for 
delete.
Binomial heaps (operations)

Operations are defined via a basic operation, called linking, of binomial trees:

Produce a $B_k$ from two $B_{k-1}$, keep heap order.

**Operations**:

- **Find min** (=1)
- **Extract tree**
- **Split tree, reverse**
- **Merge/meld**
Decrease key ($y=26 \Rightarrow y=7$)

Binomial heaps (ops cont.)

Findmin($h$): obvious

Insert($x,h$): meld a new heap with a single $B_0$ containing $x$, with $h$

deletemin($h$): Chop off the minimal root. Meld the subtrees with $h$. Update minimum pointer if needed.

delete($x,h$): Bubble up and continue like delete-min

decrease-key($x,h,\delta$): Bubble up, update min ptr if needed

All operations take $O(\log n)$ time on the worst case, except

find-min($h$) that takes $O(1)$ time.

What is the time complexity?

# $A$.len = $k$

for $i=1..n$ do Increment($A$); # $O(?)$

Increment($A$)
1. $i:=0$
2. while $i<A$.len and $A.i==1$
3. $A[i] = 0$
4. $i++$
5. if $i < A$.len
6. $A[i] = 1$

Amortized analysis

We are interested in the worst case running time of a sequence of operations.

Example: binary counter

single operation -- increment

Increment($A$)
1. $i:=0$
2. while $i<A$.len and $A.i==1$
3. $A[i] = 0$
4. $i++$
5. if $i < A$.len
6. $A[i] = 1$

• In the amortized running time analysis we pretend that very fast operations take a little bit longer than they actually do.
• This additional time is then later subtracted from the actual running time of slow operations.
• The amount of time saved for later use is measured at any given moment by a potential function.

Incrementing binary counter

<table>
<thead>
<tr>
<th>value</th>
<th>bits</th>
<th>Total cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>00</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>001</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>0001</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>0010</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>0011</td>
<td>10</td>
</tr>
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<td>6</td>
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<td>7</td>
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<tr>
<td>8</td>
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</tr>
<tr>
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<td>18</td>
</tr>
<tr>
<td>10</td>
<td>001010</td>
<td>19</td>
</tr>
<tr>
<td>11</td>
<td>001011</td>
<td>22</td>
</tr>
<tr>
<td>12</td>
<td>001100</td>
<td>23</td>
</tr>
<tr>
<td>13</td>
<td>001101</td>
<td>25</td>
</tr>
<tr>
<td>14</td>
<td>001110</td>
<td>26</td>
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<tr>
<td>15</td>
<td>001111</td>
<td>31</td>
</tr>
<tr>
<td>16</td>
<td>010000</td>
<td>32</td>
</tr>
</tbody>
</table>
Amortized analysis (Cont.)

On the worst case increment takes $O(k)$.

$k = \#\text{digits}$

What is the complexity of a sequence of increments (on the worst case)?

Define a potential of the counter:

$\Phi (c) = ?$

Amortized(increment) = actual(increment) + $\Delta \Phi$

Amortized(increment) = actual(increment) + $\Phi$

Amortized(increment) = 1+ $(1 => 0)$ + 1 - $(1 => 0)$ = $O(1)$

$\Rightarrow$ Sequence of $n$ increments takes $O(n)$ time

Amortized analysis (Cont.)

$\Sigma$Amortized(increment) = $\Sigma$actual(increment) + $\Phi_{n} - \Phi_{0}$

if $\Phi_{n} - \Phi_{0} \geq 0$

Amortized analysis (Cont.)

$\Sigma$Amortized(increment) = $\Sigma$actual(increment) + $\Phi_{n} - \Phi_{0}$

Binomial heaps - amortized ana.

$\Phi$ (collection of heaps) = $(#\text{trees})$

Amortized cost of insert $O(1)$

Amortized cost of other operations still $O(\log n)$

Binomial heaps + lazy meld

Allow more than one tree of each rank.

Meld $(h1,h2)$:

- Concatenate the lists of binomial trees.
- Update the minimum pointer to be the smaller of the minimums

$O(1)$ worst case and amortized.

Binomial heaps + lazy meld

As long as we do not do a delete-min our heaps are just doubly linked lists:

Delete-min: Chop off the minimum root, add its children to the list of trees.

Successive linking: Traverse the forest keep linking trees of the same rank, maintain a pointer to the minimum root.
Binomial heaps + lazy meld

Possible implementation of delete-min is using an array indexed by rank to keep at most one binomial tree of each rank that we already traversed.

Once we encounter a second tree of some rank we link them and keep linking until we do not have two trees of the same rank. We record the resulting tree in the array

\[
\text{Amortized}(\text{delete-min}) =
\text{(#links + max-rank) - #links} = O(\log(n))
\]

Fibonacci heaps (Fredman & Tarjan 84)

Want to do decrease-key$(x,h,\delta)$ faster than delete + insert.

Ideally in $O(1)$ time.

Why?

Dijkstra’s shortest path algorithm

Let $G = (V,E)$ be a weighted (weights are non-negative) undirected graph, let $s \in V$. Want to find the distance (length of the shortest path), $d(s,v)$ from $s$ to every other vertex.

Application #2 : Prim’s algorithm for MST

Start with $T$ a singleton vertex.

Grow a tree by repeating the following step:

Add the minimum cost edge connecting a vertex in $T$ to a vertex out of $T$.

Application #2 : Prim’s algorithm for MST

Maintain the vertices out of $T$ but adjacent to $T$ in a heap.

The key of a vertex $v$ is the weight of the lightest edge $(v,w)$ where $w$ is in the tree.

Iteration: Do a delete-min. Let $v$ be the minimum vertex and $(v,w)$ the lightest edge as above. Add $(v,w)$ to $T$. For each edge $(w,u)$ where $u \notin T$,

if key$(u) = \infty$ insert $u$ into the heap with key$(u) = w(w,u)$

if $w(w,u) <$ key$(u)$ decrease the key of $u$ to be $w(w,u)$.

With regular heaps $O(m \log(n))$.

With F-heaps $O(n \log(n) + m)$. 

Figure 26: (a) A Fibonacci heap consisting of five min heap-ordered trees and 14 nodes. The dashed line indicates the root list. The minimum node of the heap is the node containing the key 3. The three marked nodes are blackened. The potential of this particular Fibonacci heap is 5+2+3 = 10. (b) A more complete representation showing pointers (up arrows), child (down arrows), and left and right (side-arrows). These details are omitted in the remaining figures in this chapter, since all the information shown here can be determined from what appears in part (a).
Insert (left from root)

Finding the minimum node

- The minimum node of a Fibonacci heap $H$ is given by the pointer $\min[H]$, so we can find the minimum node in $O(1)$ actual time. Because the potential of $H$ does not change, the amortized cost of this operation is equal to its $O(1)$ actual cost.

**Figure 21.3 The action of FIB-HEAP-EXTRACT-MIN.**

A Fibonacci heap $H$. (a) The situation after the minimum node is removed from the root list and its children are added to the root list. Each part shows the heap at a particular moment in time. (b) The array $A$ and the trees after each of the first three iterations of the for loop of lines 3-13 of the procedure CONSOLIDATE. Each part shows the heap at a particular moment in time. (c) The array $A$ and the trees after each of the first three iterations of the for loop of lines 3-13 of the procedure CONSOLIDATE. Each part shows the heap at a particular moment in time. (d) The array $A$ and the trees after each of the first three iterations of the for loop of lines 3-13 of the procedure CONSOLIDATE. Each part shows the heap at a particular moment in time. (e) The array $A$ and the trees after each of the first three iterations of the for loop of lines 3-13 of the procedure CONSOLIDATE. Each part shows the heap at a particular moment in time. (f) The array $A$ and the trees after each of the first three iterations of the for loop of lines 3-13 of the procedure CONSOLIDATE. Each part shows the heap at a particular moment in time. (g) The array $A$ and the trees after each of the first three iterations of the for loop of lines 3-13 of the procedure CONSOLIDATE. Each part shows the heap at a particular moment in time. (h) The array $A$ and the trees after each of the first three iterations of the for loop of lines 3-13 of the procedure CONSOLIDATE. Each part shows the heap at a particular moment in time. (i) The array $A$ and the trees after each of the first three iterations of the for loop of lines 3-13 of the procedure CONSOLIDATE. Each part shows the heap at a particular moment in time. (j) The array $A$ and the trees after each of the first three iterations of the for loop of lines 3-13 of the procedure CONSOLIDATE. Each part shows the heap at a particular moment in time. (k) The array $A$ and the trees after each of the first three iterations of the for loop of lines 3-13 of the procedure CONSOLIDATE. Each part shows the heap at a particular moment in time. (l) The array $A$ and the trees after each of the first three iterations of the for loop of lines 3-13 of the procedure CONSOLIDATE. Each part shows the heap at a particular moment in time. (m) Fibonacci heap $H$ after reconstruction of the root list from the array $A$ and determination of the new $\min[H]$ pointer.
Suggested implementation for decrease-key(h,δ):
If x with its new key is smaller than its parent, cut the subtree rooted at x and add it to the forest. Update the minimum pointer if necessary.

Two calls of FIB-HEAP-DECREASE-KEY.
(a) The initial Fibonacci heap. (b) The node with key 46 has its key decreased to 15. The node becomes a root, and its parent (with key 24), which had previously been unmarked, becomes marked. (c) The node with key 35 has its key decreased to 5. It becomes a root. Its parent (with key 26), which had previously been marked, becomes unmarked. The root with key 26 is cut from its parent and made an unmarked root in part (d). Another cascading cut occurs, since the node with key 24 is marked as well. This node is cut from its parent and made an unmarked root in (e). The cascading cuts stop at this point, since the node with key 7 is a root. Even if this node were not a root, the cascading cuts would stop, since it is unmarked. The result of the FIB-HEAP-DECREASE-KEY operation is shown in part (e), with min[H] pointing to the new minimum node.

Decrease-key (cont.)

Does it work?
Obs1: Trees need not be binomial trees any more.
Do we need the trees to be binomial?
Where have we used it?

In the analysis of delete-min we used the fact that at most log(n) new trees are added to the forest. This was obvious since trees were binomial and contained at most n nodes.

Decrease-key (cont.)

Such trees are now legitimate.
So our analysis breaks down.

Fibonacci heaps (cont.)

We shall allow non-binomial trees, but will keep the degrees logarithmic in the number of nodes.

Rank of a tree = degree of the root.
Delete-min: do successive linking of trees of the same rank and update the minimum pointer as before.
Insert and meld also work as before.
Fibonacci heaps (delete)

Delete(x,h) : Cut the subtree rooted at x and then proceed with cascading cuts as for decrease key.
Chop off x from being the root of its subtree and add the subtrees rooted by its children to the forest.
If x is the minimum node do successive linking.

- The potential of a Fibonacci heap is given by
- Potential = \( t + 2m \) where \( t \) is the number of trees in the Fibonacci heap, and \( m \) is the number of marked nodes. A node is marked if at least one of its children was cut since this node was made a child of another node (all roots are unmarked).

Fibonacci heaps (analysis)

Want everything to be \( O(1) \) time except for delete and delete-min.

\[ \Phi (\text{collection of heaps}) = \#(\text{trees}) + 2\#(\text{marked nodes}) \]

\[ \text{Actual(decrease-key)} = O(1) + \#(\text{cascading cuts}) \]
\[ \Delta \Phi (\text{decrease-key}) = O(1) - \#(\text{cascading cuts}) \]

\[ \Rightarrow \text{amortized(decrease-key)} = O(1) \]

Fibonacci heaps (analysis)

Cascading cuts and successive linking will pay for themselves. The only question is what is the maximum degree of a node?

How many trees are being added into the forest when we chop off a root?

Fibonacci heaps (analysis)

Lemma 1 : Let x be any node in an F-heap. Arrange the children of x in the order they were linked to x, from earliest to latest. Then the i-th child of x has rank at least i-2.

\[ x \]
\[ 2 \]
\[ 1 \]

Proof:
When the i-th node was linked it must have had at least i-1 children.
Since then it could have lost at most one.

Fibonacci heaps (analysis)

Corollary 1 : A node x of rank k in a F-heap has at least \( \phi^k \) descendants, where \( \phi = (1 + \sqrt{5})/2 \) is the golden ratio.

Proof:
Let \( s_k \) be the minimum number of descendants of a node of rank k in a F-heap.
By Lemma 1 \( s_k \geq s_{k-1} + 2 \)

\[ s_0 = 1, s_1 = 2 \]
24.3.2011

Fibonacci heaps (analysis)

Proof (cont):
Fibonacci numbers satisfy
\[ F_{k+2} = \sum_{i=2}^{k} F_i + 2, \text{ for } k \geq 2, \text{ and } F_2 = 1 \]
so by induction \( s_k \geq F_{k+2} \)

It is well known that \( F_{k+2} \geq \phi^k \)

It follows that the maximum degree \( k \) in a F-heap with \( n \) nodes is such that
\[ \phi^k \leq n \]
so \( k \leq \frac{\log(n)}{\log(\phi)} = 1.4404 \log(n) \)

**Make-Fibonacci-Heap**

\[
\begin{align*}
  n[H] &:= 0 \\
  \text{min}[H] &:= \text{NIL} \\
  \text{return } H
\end{align*}
\]

**Fibonacci-Heap-Minimum**

\[
\text{return } \text{min}[H]
\]

**CONSOLIDATE**

\[
\begin{align*}
  \text{for } i &:= 0 \text{ to } D(n[H]) \\
  &\text{Do } A[i] := \text{NIL} \\
  \text{for each node } w \text{ in the root list of } H \\
  &\text{do } x := w \\
  &\text{d := degree}[x] \\
  &\text{while } A[d] \neq \text{NIL} \\
  &\text{do } y := [d] \\
  &\text{if key}[y] > \text{key}[x] \\
  &\text{then exchange } x \leftrightarrow y \\
  &\text{Fibonacci-Heap-Link}(H, x, y) \\
  &A[d] := \text{NIL} \\
  &d := d + 1 \\
  &A[d] := x \\
  &\text{min}[H] := \text{NIL} \\
  \text{for } i := 0 \text{ to } D(n[H]) \\
  &\text{do if } A[i] \neq \text{NIL} \\
  &\text{then add } A[i] \text{ to the root list of } H \\
  &\text{if min}[H] = \text{NIL} \text{ or } \text{key}[A[i]] > \text{key}[\text{min}[H]] \\
  &\text{then } \text{min}[H] := A[i]
\end{align*}
\]

**Fibonacci-Heap-Union**

\[
\begin{align*}
  H &:= \text{Make-Fibonacci-Heap()} \\
  \text{min}[H] &:= \text{min}[H1] \\
  \text{Concatenate the root list of } H2 \text{ with the root list of } H \\
  \text{if } (\text{min}[H1] = \text{NIL}) \text{ or } (\text{min}[H2] \neq \text{NIL} \text{ and } \text{min}[H2] < \text{min}[H1]) \\
  &\text{then } \text{min}[H] := \text{min}[H2] \\
  &n[H] := n[H1] + n[H2] \\
  \text{free the objects } H1 \text{ and } H2 \\
  \text{return } H
\end{align*}
\]
Fibonacci-Heap-Insert\((H, x)\)
\[
\begin{align*}
degree[x] & := 0 \\
p[x] & := \text{NIL} \\
child[x] & := \text{NIL} \\
left[x] & := x \\
right[x] & := x \\
mark[x] & := \text{FALSE} \\
& \text{concatenate the root list containing } x \text{ with root list } H \\
& \text{if } \min[H] = \text{NIL} \text{ or } \text{key}[x] < \text{key}[\min[H]] \\
& \quad \text{then } \min[H] := x \\
n[H] & := n[H]+1
\end{align*}
\]

Fibonacci-Heap-Extract-Min\((H)\)
\[
\begin{align*}
z & := \min[H] \\
& \text{if } x = \text{NIL} \\
& \quad \text{then for each child } x \text{ of } z \\
& \quad \quad \text{do add } x \text{ to the root list of } H \\
& \quad \quad \quad p[x] := \text{NIL} \\
& \quad \quad \quad \text{remove } z \text{ from the root list of } H \\
& \quad \quad \quad \text{if } z = \text{right}[z] \\
& \quad \quad \quad \text{then } \min[H] := \text{NIL} \\
& \quad \quad \text{else } \min[H] := \text{right}[z] \\
& \quad \quad \text{CONSOLIDATE}(H) \\
& \quad \quad n[H] := n[H]-1 \\
& \quad \quad \text{return } z
\end{align*}
\]

Fibonacci-Heap-Decrease-Key\((H, x, k)\)
\[
\begin{align*}
& \text{if } k > \text{key}[x] \\
& \quad \text{then error } "\text{new key is greater than current key}" \\
& \quad \text{key}[x] := k \\
& y := p[x] \\
& \text{if } y = \text{NIL} \text{ and } \text{key}[x] < \text{key}[y] \\
& \quad \text{then } \text{CUT}(H, x, y) \\
& \quad \text{CASCADING-CUT}(H, y) \\
& \quad \text{if } \text{key}[x] < \text{key}[\min[H]] \\
& \quad \quad \text{then } \min[H] := x \\
& \text{CUT}(H, x) \\
& \text{Remove } x \text{ from the child list of } y, \text{ decrementing } \text{degree}[y] \\
& \text{Add } x \text{ to the root list of } H \\
& p[x] := \text{NIL} \\
& \text{mark}[x] := \text{FALSE} \\
& \text{CASCADING-CUT}(H) \\
& z := p[y] \\
& \text{if } z = \text{NIL} \\
& \quad \text{if } \text{mark}[y] = \text{FALSE} \\
& \quad \quad \text{then } \text{mark}[y] := \text{TRUE} \\
& \quad \quad \text{else } \text{CUT}(H, y, z) \\
& \quad \text{CASCADING-CUT}(H, z)
\end{align*}
\]

Fibonacci-Heap-Delete\((H, x)\)
Fibonacci-Heap-Decrease-Key\((H, x, -\infty)\)
Fibonacci-Heap-Extract-Min\((H)\)

Summary of running times

<table>
<thead>
<tr>
<th>Operation</th>
<th>Linked List</th>
<th>Balanced Binary Tree</th>
<th>(Min)+Heap</th>
<th>Fibonacci Heap</th>
<th>Brodal Queue</th>
</tr>
</thead>
<tbody>
<tr>
<td>insert</td>
<td>O(1)</td>
<td>O(\log n)</td>
<td>O(\log n)</td>
<td>O(1)</td>
<td>O(1)</td>
</tr>
<tr>
<td>access(\min)</td>
<td>O(n)</td>
<td>O(\log n) or O(1)**</td>
<td>O(1)</td>
<td>O(1)</td>
<td>O(1)</td>
</tr>
<tr>
<td>decrease(\min)</td>
<td>O(n)</td>
<td>O(\log n)</td>
<td>O(\log n)*</td>
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<tr>
<td>decrease(\max)</td>
<td>O(1)</td>
<td>O(\log n)</td>
<td>O(\log n)</td>
<td>O(1)**</td>
<td>O(1)</td>
</tr>
<tr>
<td>delete</td>
<td>O(n)</td>
<td>O(\log n)</td>
<td>O(\log n)*</td>
<td>O(\log n)</td>
<td>O(\log n)</td>
</tr>
<tr>
<td>merge</td>
<td>O(1)</td>
<td>O(m \log(n+m))</td>
<td>O(m \log(n+m))</td>
<td>O(1)</td>
<td>O(1)</td>
</tr>
</tbody>
</table>

(*Anamorized time)  
(**With trivial modification to the conventional Binary tree)
van Emde Boas tree

- A van Emde Boas tree (or van Emde Boas priority queue), also known as a vEB tree, is a tree data structure which implements an associative array with m-bit integer keys. It performs all operations in $O(\log m)$ time. Notice that $m$ is the size of the keys — therefore $O(\log m)$ is $O(\log \log n)$ in a full tree, exponentially better than a self-balancing binary search tree. They also have good space efficiency when they contain a large number of elements, as discussed below. They were invented by a team led by Peter van Emde Boas in 1977.[1]

---

PQ – Structure (Cont’d)

- Subset $S \subseteq \{1, \ldots, n\}$ Representation
  - Mark leaves in $S$ and all nodes on the paths from root to the marked leaves.

---

PQ – (Cont’d)

- Insert($i$)
- Delete($i$)
- Member($i$)
- Min
- Predecessor
Sketches of Algorithms

- Insert(i)
- Delete(i)
- Member(i)
- Min
- Predecessor

Sketches of Algorithms

- Insert(i)
- Delete(i)
- Member(i)
- Min
- Predecessor

Sketches of Algorithms

- Insert(i)
- Delete(i)
- Member(i)
- Min
- Predecessor

Sketches of Algorithms

- Insert(i)
- Delete(i)
- Member(i)
- Min
- Predecessor