COS 423

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Class Notes: Disjoint Set Union (see Chapter 22, CLR)

Problem: Maintain a collection of disjoint sets.

Two operations: *find* the set containing a given element;
unite two sets into one (destructively).

Approach: "Canonical element" method: for each set, the algorithm maintains a canonical element (arbitrary but unique), with which any desired information about the set is stored.

Two low-level operations:

find (x): given element x, return the canonical element of the set containing x;

link(x, y): given canonical elements x and y, destructively unite the sets containing them, and make x or y the canonical element of the new set. (Do nothing if $x = y$.)

Then *unite* can be implemented as follows:

unite (x, y) : unite the sets containing (arbitrary) elements x and y (if they differ)

unite $(x, y) =$ link (*find* (x), *find* (y))

Tree-based implementation: the elements of each set form a tree, with each node pointing to its parent, via a "p" pointer. Each tree root points to itself.

Assume n singleton sets initially ($p(x) = x$ for every x initially); m total finds, interspersed with links; $m \geq n$.

To perform *find*, follow parent pointers to tree root. To perform *compression* after a find, make every node on the find path point directly to the root.

Linking by rank (rank is maximum length, in *edges*, of an uncompressed path from a descendant)

$r\ (x) = 0$ for every x initially.

To link x and y, make the smaller-ranked root point to the larger; in case of a tie, increase the rank of the new root by one.

Question: What is the total time for m finds interspersed with links?

Answer: $O(m\alpha(n))$, where

$A_0(x) = x + 1$ for $x \geq 1$

$A_{k+1}(x) = A_k^{x+1}(x)$ for $x \geq 1$ $\left(A_k^0(x) = x,\ A_k^{i+1}(x) = A_k(A_k^i(x))\right)$

$\alpha(n) =$ the smallest k such that $A_k(1) \geq n$

From these definitions, $A_1(x) = 2x + 1,\ A_2(x) > 2^{x+1},\ A_3(x) > \left.2^{2^{2^{\cdot^{\cdot^{\cdot^{2}}}}}}\right\}x+1,$ and $\alpha(n)$ grows *very* slowly.

Exercise: Prove that $A_k(x)$ is an increasing function of both k and x.

To prove the $O(m\alpha(n))$ bound we use an amortized analysis.

Observe that the rank of a node x starts at 0, can increase but not decrease while x is a tree root, and remains constant once x is a nonroot. Observe also that $r(p(x)) > r(x)$. Once x has a parent, $r(x)$ is constant, but $r(p(x))$ can increase (but not decrease), either because $p(x)$ changes due to a compression or $r(p(x))$ changes due to a link. The maximum node rank is at most $n - 1$. (Why?) (Actually, it is at most lgn, but we won't use this.)

We will define a potential function that assigns a non-negative integer potential of at most $\alpha(n)r(x)$ to each node x; the total potential is the sum of all the node potentials.

Any tree root x has potential $\alpha(n)r(x)$. (Thus the total initial potential is 0.) Let x be a nonroot with $r(x) \geq 1$. Define the *level* of x, denoted by $k(x)$, to be the largest k for which $r(p(x)) \geq A_k(r(x))$.

We have $A_0(r(x)) = r(x) + 1 \leq r(p(x))$ and $A_{\alpha(n)}(r(x)) \geq A_{\alpha(n)}(1) \geq n > n - 1 \geq r(p(x))$. Thus $k(x)$ is well-defined and $0 \leq k(x) < \alpha(n)$. Furthermore, since $r(p(x))$ can never decrease, $k(x)$ can never decrease, only increase.

Define the *index* of x, denoted by $i(x)$, to be the largest i for which $r(p(x)) \geq A^i_{k(x)}(r(x))$.

We have $A^1_{k(x)}(r(x)) = A_{k(x)}(r(x)) \leq r(p(x))$ by the definition of $k(x)$, and $A^{r(x)+1}_{k(x)}(r(x)) = A_{k(x)+1}(r(x)) > r(p(x))$, by the definitions of A_k and $k(x)$. Thus $i(x)$ is well-defined and $1 \leq i(x) \leq r(x)$. Also, since $r(p(x))$ can never decrease, $i(x)$ cannot decrease unless $k(x)$ increases: while $k(x)$ remains constant, $i(x)$ can only increase or stay the same.

Now we are ready to define the potential of a node x.

$$
\begin{aligned}
\phi(x) &= \alpha(n)r(x) \text{ if } x \text{ is a root or } r(x) = 0 \\
\phi(x) &= (\alpha(n) - k(x))r(x) - i(x) \text{ if } x \text{ is a nonroot and } r(x) > 0
\end{aligned}
$$

We define the total potential Φ to be the sum over all nodes x of $\phi(x)$.

Let us show that $0 \leq \phi(x) \leq \alpha(n)r(x)$ for every node x. This is obvious if x is a root or $r(x) = 0$. Suppose x is a nonroot and $r(x) > 0$. Since $k(x) \leq \alpha(n) - 1$ and $i(x) \leq r(x)$, $\phi(x) \geq r(x) - r(x) \geq 0$. Since $k(x) \geq 0$ and $i(x) \geq 1$, $\phi(x) \leq \alpha(n)r(x) - 1$.

With this definition of potential, the potential of a nonroot node x with $r(x) \geq 1$ can never increase, and it drops by at least one if either $k(x)$ or $i(x)$ changes. This is because, if $k(x)$ remains constant, $i(x)$ cannot decrease, and if $k(x)$ increases, $i(x)$ can decrease but only by at most $r(x) - 1$, whereas the increase in $k(x)$ causes the first term in the potential to drop by at least $r(x)$.

What remains is to show that the amortized cost of a find or link is $O(\alpha(n))$. First consider a link, say *link* (x, y). Without loss of generality suppose the link makes y the new root. The actual cost of the link is (order of) one. The only nodes whose potentials can change because of the link are x, and y, and other children of y. The potentials of x and other children of y cannot increase, only stay the same or decrease, and the potential of y stays the same or increases by $\alpha(n)$, since $r(y)$ stays the same or increases by one. Thus the increase of Φ due to the link is at most $\alpha(n)$, and the amortized cost of the link is at most $\alpha(n) + 1$.

Consider a find with compression. The actual cost of the find is (order of) the number of nodes on the find path. No node can have its potential increase as a result of the find. We shall show that if ℓ is the number of nodes on the find path, at least $\max\{0, \ell - (\alpha(n) + 2)\}$ of these nodes have their potential decrease (by at least one) as a result of the compression. This implies that the amortized cost of the find is at most $\alpha(n) + 2$.

Specifically, let x be a node on the find path such that $r(x) > 0$ and x is followed on the find path by another nonroot node y such that $k(y) = k(x)$. All but at most $\alpha(n) + 2$ nodes on the find path satisfy this constraint; those that do not are the first node on the path (if it has rank zero), the last node on the path (the root), and the last nonroot node on the path of level k, for each possible k in the range $0 \leq k < \alpha(n)$.

Let $k = k(x) = k(y)$. Before the compression, $r(p(x)) \geq A_k^{i(x)}(r(x)), r(p(y)) \geq A_k(r(y))$, and $r(y) \geq r(p(x))$. These inequalities imply $r(p(y)) \geq A_k(r(y)) \geq A_k(r(p(x))) \geq A_k(A_k^{i(x)}(r(x))) = A_k^{i(x)+1}(r(x))$, which means that the compression causes $i(x)$ to increase or $k(x)$ to increase, in either case decreasing $\phi(x)$.