Notes on Kruskal's Algorithm for Minimal Spanning Tree

In Kruskal's algorithm (§23.2) the edges are ordered $e_1, \ldots, e_E$ by of weight and e_i is added to the tree if and only if its addition does not cause a cycle. The data structure that does this efficiently is covered in detail in Chapter 21, which we are not covering. Instead, these notes give a specific implementation of the algorithm. Assume the edges have already been ordered by weight and x_i, y_i are the vertices of e_i. To each vertex x we have functions $\pi(x)$ and $SIZE(x)$, initially all $\pi(x) \leftarrow x$ and all $SIZE(x) \leftarrow 1$.

For $i = 1$ to E we set (for notational convenience) $x \leftarrow x_i$, $y \leftarrow y_i$ and do the following:

WHILE $\pi(x) \neq x$
    $x \leftarrow \pi(x)$ (*going down the stairs*)
WHILE $\pi(y) \neq y$
    $y \leftarrow \pi(y)$ (*going down the stairs*)
IF $x \neq y$ then DO
    IF $SIZE(x) \leq SIZE(y)$ then DO
        $\pi(x) \leftarrow y$
        $SIZE(y) \leftarrow SIZE(y) + SIZE(x)$
    OTHERWISE DO
        $\pi(y) \leftarrow x$
        $SIZE(x) \leftarrow SIZE(x) + SIZE(y)$
    Add e_i to Minimal Spanning Tree

At any time the $\pi(x)$ will give a rooted forest with $\pi(x) = x$ exactly when x is a root. In that case $SIZE(x)$ will be the size of the forest. Certain edges will have already been put in the Minimal Spanning Tree so that the structure will be a forest. That forest and the forest given by $\pi(x)$ will have the same components (though they may have different edges).

Example. $e_1 = (a, c), e_2 = (c, b), e_3 = (d, e), e_4 = (a, d), e_5 = (b, d)$. With $i = 1$ we add e_1 to tree, $\pi(a) \leftarrow c$ and $SIZE(c) \leftarrow 2$. With $i = 2$ we add e_2 to tree, as $SIZE(c) > SIZE(b)$ we set $pi(b) \leftarrow c$ and $SIZE(c) \leftarrow 3$. With $i = 3$ we add e_3 to tree, $\pi(d) \leftarrow e$ and $SIZE(e) \leftarrow 2$. Now $i = 4$ so $x \leftarrow a; y \leftarrow d$. The WHILE parts trace x down to its root c and y down to its root e. As $SIZE(c) > SIZE(e)$ we set $\pi(e) \leftarrow c$, $SIZE(c) \leftarrow 5$ and add e_4 to the tree. Note that the current state of the Minimal Spanning Tree and the forest given by π have different edges but the same components. Now with $i = 5$, $x \leftarrow b; y \leftarrow e$. Both x, y trace down with the WHILE loops to the same c so we do nothing and e_5 is not added to the tree.

To analyze the time we note that the process is done E times, so we analyze the process with a particular $x = x_i, y = y_i$. The key aspect to the time is we must iterate $\pi(x) \leftarrow x$ until reaching a root. (Similarly for y.) At first blush, this seems like it might take time V. (V is number of vertices.) *However,* here we use the fact that when we earlier considered an edge x, y and we moved them down to their roots we then reset $\pi(x) \leftarrow y$ where $SIZE[y]$ had been bigger than $SIZE[x]$. Now the new $SIZE[y]$ became the old $SIZE[x]+SIZE[y]$. That is, the new $SIZE[y]$ is at least double the old $SIZE[x]$. As x is no longer a root its value of $SIZE[x]$ will never change. The value of $SIZE[y]$ may change later, but it can only get larger. Hence we will have $2 \cdot SIZE[x] \leq SIZE[y]$ forevermore. Therefore, as we look at a path $x, \pi(x), \pi(\pi(x)), \ldots$ the value $SIZE(\cdot)$ at least doubles each iteration. Therefore the path can only be of length $\log V$. This is a big savings over the length V without this aspect. Now the process with a particular x, y takes time $O(\log V)$ and therefore the total time is $O(E \log V)$.

`Path Compression:` (This is extra material and **not** on the final!) Before we move "down the stairs" we save, temporarily, the original value of x. (same for y) with

$originalx \leftarrow x$

Then we go "down the stairs" to the new value of x. Now we go back up to $originalx$ and reset the entire path to arrow the new x:

$z \leftarrow originalx$

$\pi[z] \leftarrow x$

WHILE $\pi[z] \neq z$

$\pi[z] \leftarrow x$

$z \leftarrow \pi[z]$

That is, the entire path from $originalx$ to x is now pointing directly to x. This has effectively doubled the time, as we go down the WHILE loop twice. However, when later in the program we have a WHILE loop that hits $originalx$ it will jump directly to x. That is, the path has been *compressed.* Analysis of path compression is remarkably subtle (mathematicians love it!) but lets just say that it gives an improved running time for MST when n is really large.