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Union-Find

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1 Theory

Definition 1.1 (Reachability)**.** A node v is *reachable* from a node u in a directed graph $G = (V, E)$ if there exists a sequence of directed edges $e_1, e_2, \ldots, e_m \in E$ where $m \geq 1$ and $e_i = (v_{i-1}, v_i)$ for $1 \leq i \leq m$, such that $v_0 = u$ and $v_m = v$. We denote this by $u \rightsquigarrow v$.

Definition 1.2 (Cycle)**.** A cycle in a directed graph $G = (V, E)$ has a cycle if there exists $v \in V$ such that $v \rightsquigarrow v$.

Definition 1.3 (Forest)**.** A forest is a directed graph $F = (V, E)$ where V is a set of vertices and $E \subseteq V \times V$ is a set of directed edges such that:

1. There are no cycles $v \not\rightsquigarrow v$ for all $v \in V$, and
2. each node has at most one parent i.e. for all $(u, v_1), (u, v_2) \in E$ it holds that $v_1 = v_2$.

Definition 1.4 (Root)**.** A node $v \in V$ in a forest $F = (V, E)$ is a root if it has no parent. This is defined as the predicate:

$$\mathcal{R}_F(v) : v \not\rightsquigarrow u \text{ for all } u \in V$$

Definition 1.5 (Tree)**.** A tree is a forest $T = (V, E)$ where there exists a unique root $r \in V$ such that $v \rightsquigarrow r$ for all $v \in V \backslash \{r\}$.

Proposition 1.1 (Forest Root Count)**.** A forest $F = (V, E)$ where $|V| = n$ and $|E| = n - k$ has k roots.

Proof. Let $F = (V, E)$ be a forest where $|V| = n$ and $|E| = n - k$. By the second property of a forest then $n - k$ vertices must have a parent. Since there are n vertices in total it follows that there are exactly k vertices $r_1, r_2, \ldots, r_k \in V$ that has no parent. Hence there are exactly k roots in F. □

Proposition 1.2 (Roots Path Exist)**.** In a forest $F = (V, E)$ for each element $v \in V$ there exists at least one root $r \in V$ such that $\mathcal{R}_F(r)$ and either $v \rightsquigarrow r$ or $v = r$.

Proof. Let $F = (V, E)$ be a forest and let $v \in V$ be an arbitrary element in V. By proposition 1.1 there exists at least one root $r \in V$ such that $\mathcal{R}_F(r)$. This can be shown by structural induction on a vertex $v \in V$ that any $p \in V$ such that $v \rightsquigarrow p$ has a path $p \rightsquigarrow r$.

- If v is a root then we are done.
- By induction hypothesis v has a path to a root $r \in V$ such that $\mathcal{R}_F(r)$. Since v is not a root it must have a parent $p \in V$ such that $(v, p) \in E$. Since $v \rightsquigarrow r$, $v \rightsquigarrow p$ and v only has one parent it follows that $p \rightsquigarrow r$. Hence $p \rightsquigarrow r$ for some root $r \in V$ such that $\mathcal{R}_F(r)$.

□

Proposition 1.3 (Forest Edge Limit)**.** A forest $F = (V, E)$ where $|V| = n$ and $|E| > n - 1$ is not a forest.

Proof. Let $F = (V, E)$ be a forest where $|V| = n$ and $|E| > n - 1$. By proposition 1.1 a forest with $n - 1$ has exactly one root, so it is a tree. By adding one more edge to the tree it must make one vertex have two parents. Or since every vertex $v \in V$ has a path to the root $r \in V$ it must create a cycle $v \rightsquigarrow v$ for some $v \in V$. In both cases it contradicts the properties of a forest. □

Definition 1.6 (Representative)**.** The representative of an element $v \in V$ in a forest $F = (V, E)$ is the root $r \in V$ such that there is a path from v to r. This is defined as the function:

$$\rho_F(v) := r \text{ where } r \in V \wedge \mathcal{R}_F(r) \wedge (v \rightsquigarrow r \vee v = r)$$

Proposition 1.4 (Unique Representative)**.** In a forest $F = (V, E)$ each element $v \in V$ has a unique representative $\rho_F(v)$.

Proof. Let $F = (V, E)$ be a union-find structure and let $v \in V$ be an arbitrary element in V. By proposition 1.2 there exists at least one root $r \in V$ such that $\mathcal{R}_F(r)$ and $v \rightsquigarrow r$. Now assume that there exists another root $r' \in V$ such that $\mathcal{R}_F(r')$ and $v \rightsquigarrow r'$. Since F is a forest it follows by the second property of a forest that $r = r'$ hence the representative is unique. □

Definition 1.7 (Tree Set)**.** The set of vertices of the same tree $\mathcal{E}_F(v)$ in a forest $F = (V, E)$ is defined as:

$$\mathcal{E}_F(v) := \{u : u \in V \wedge \rho_F(u) = \rho_F(v))\}$$

Definition 1.8 (Partition)**.** The set $P \subseteq \mathbb{P}(S)$ is a partition of a set S if:

1. $a \neq \emptyset$ for all $a \in P$
2. $a \cap b = \emptyset$ for all $a, b \in P$ where $a \neq b$

3. $\bigcup_{a \in P} a = S$

Proposition 1.5 (Forest Partition)**.** A forest $F = (V, E)$ is a partition of V for the following set:

$$\{\mathcal{E}_F(v) : v \in V\}$$

Proof. Let $F = (V, E)$ be a forest. We will show that the set in the proposition is a partition of V by showing that it satisfies the three properties in definition 1.8.

1. By definition of $\mathcal{E}_F(v)$ it can not be empty since for $\mathcal{E}_F(v)$ then $\rho_F(v) = \rho_F(v)$. Hence $\mathcal{E}_F(v) \neq \emptyset$ for all $v \in V$.

2. Let a and b be two arbitrary elements in the set such that $a \neq b$. By definition of a and b there exists $v_1, v_2 \in V$ such that $a = \{u : u \in V \wedge \rho_F(u) = \rho_F(v_1)\}$ and $b = \{u : u \in V \wedge \rho_F(u) = \rho_F(v_2)\}$. Since $a \neq b$ it follows that $\rho_F(v_1) \neq \rho_F(v_2)$ since otherwise $a = b$, hence $a \cap b = \emptyset$.

3. Let v be an arbitrary element in V. By proposition 1.2 there exists a root $r \in V$ such that $\mathcal{R}_F(r)$ and $v \rightsquigarrow r$ or $v = r$. By definition of the representative it follows that $\rho_F(v) = r$. Now let $a = \{u : u \in V \wedge \rho_F(u) = \rho_F(v)\}$. By definition of a it follows that $v \in a$. Since v was arbitrary it follows that $\bigcup_{a \in P} a = V$.

$\square$

Definition 1.9 (Same Tree Relation)**.** The relation $\sim_F$ on a forest F is defined as:

$$u \sim_F v :\iff u \in \mathcal{E}_F(v)$$

Corollary 1.1 (Same Tree Relation is an Equivalence Relation)**.** The relation $\sim_F$ on a forest F is an equivalence relation due to $\{\mathcal{E}_F(v) : v \in V\}$ being a partition of V. by proposition 1.5.

Definition 1.10 (Forests with Equivalent Tree Sets)**.** Two forests $F = (V, E)$ and $F' = (V', E')$ have equivalent tree sets $F \cong F'$ if:

- Vertices are the same $V = V'$.
- The tree sets are equivalent $\mathcal{E}_F(v) = \mathcal{E}'_F(v)$ for all $v \in V$.

Definition 1.11 (Tree Union)**.** The tree union of two elements v and u for a forest $F = (V, E)$ is such that $v \sim_{F'} u$ in a new forest $F' = (V', E')$ and F' satify the following properties:

1. $\mathcal{E}_{F'}(v) = \mathcal{E}_{F'}(u) = \mathcal{E}_F(v) \cup \mathcal{E}_F(u)$ and
2. $\mathcal{E}_{F'}(w) = \mathcal{E}_F(w)$ for all $w \in V \backslash (\mathcal{E}_F(v) \cup \mathcal{E}_F(u))$.

Proposition 1.6 (Tree Union)**.** Let forest $F = (V, E)$, $p = \rho_F(u)$ be the representative of u and let $q = \rho_F(v)$ be the representative of v where $q \neq p$. Then defined F' as:

$$F' := (V, E \cup \{(q, p)\})$$

Then $u \sim_{F'} v$ in F' and F' will satisfy the properties of a tree union.

Proof. Let $F = (V, E)$, $p = \rho_F(u)$ be the representative of u and let $q = \rho_F(v)$ be the representative of v. By definition q will have parent p in F' and since q is a root it has no parent then F' is a forest. Now for all $w \in \mathcal{E}_F(q)$ it holds that $w \rightsquigarrow q$ or $q = w$ and since $q \rightsquigarrow p$ it follows that $w \rightsquigarrow p$. Hence $w \in \mathcal{E}_{F'}(p)$ for all $w \in \mathcal{E}_F(q)$ and trivially $w \in \mathcal{E}_{F'}(p)$ for all $w \in \mathcal{E}_F(p)$ so it follows that $\mathcal{E}_{F'}(v) = \mathcal{E}_{F'}(u) = \mathcal{E}_F(v) \cup \mathcal{E}_F(u)$. Now let $w \in V \backslash (\mathcal{E}_F(v) \cup \mathcal{E}_F(u))$ be an arbitrary element. Since $w \not\rightsquigarrow p$, $w \neq p$, $w \not\rightsquigarrow q$, and $w \neq q$ it follows that w has the same representative in F' as in F hence $\mathcal{E}_{F'}(w) = \mathcal{E}_F(w)$. $\square$

Definition 1.12 (Conflict-free Set)**.** Let forest F be a forest, $X \subseteq V \times V$ be a set of pairs of elements in V and $Y = \{(\rho_F(u), \rho_F(v)) : (u, v) \in X\}$. Then X is a conflict-free set in F if (V, Y) is a forest.

Proposition 1.7. Let forest $F = (V, E)$ be a forest and let $X \subseteq V \times V$ be a conflict-free set in F where $|X| = n$. Then defining the following forests:

$$F_0 := F$$
$$F_i := (V, E_{i-1} \cup \{(\rho_F(u_i), \rho_F(v_i))\}) \text{ for } (u_i, v_i) \in X \text{ and } 1 \leq i \leq n$$

Then F_n is a forest.

Proof. Let forest $F = (V, E)$ be a forest, $X \subseteq V \times V$ be a conflict-free set in F and $Y = \{(\rho_F(u), \rho_F(v)) : (u, v) \in X\}$. We will show that F_n is a forest by induction on i.

- Base case: If $i = 0$ then $F_i = F_0 = F$ which is a forest.

- Induction hypothesis: Assume that F_{i-1} is a forest for all $1 \leq i < n$. Let $(y, w) \in Y$ be the pair corresponding to $(u_i, v_i) \in X$ such that $(\rho_F(u_i), \rho_F(v_i)) = (y, w) \in Y$. We know that $y \neq y'$ for all $(y', w') \in Y \backslash \{(y, w)\}$ since otherwise (V, Y) would not be a forest and X would not be a conflict-free set in F. So y will only have one parent in F_i since it only appears once as a child in Y. By definition all of the edges in Y consists of roots in F, and since (V, Y) is a forest there are no cycles $y \not\rightsquigarrow y$ for all $y \in V$ in F_i. Hence F_i is a forest.

Thus by induction F_n is a forest. $\square$

Proposition 1.8. Let forest F be a forest and let $X \subseteq V \times V$ be a conflict-free set in F where $|X| = n$. Then defining the following forests:

$$\begin{aligned}
F_0 &:= F \\
F_i &:= (V, E_{i-1} \cup \{(\rho_F(u_i), \rho_F(v_i))\}) \text{ for } (u_i, v_i) \in X \text{ and } 1 \leq i \leq n \\
G_0 &:= F \\
G_j &:= (V, E_{i-1} \cup \{(\rho_{G_{j-1}}(u_j), \rho_{G_{j-1}}(v_j))\}) \text{ for } (u_j, v_j) \in X \text{ and } 1 \leq j \leq n
\end{aligned}$$

Then $F_n \cong G_n$.

Proof. Let forest F be a forest, $X \subseteq V \times V$ be a conflict-free set in F and $Y = \{(\rho_F(u), \rho_F(v)) : (u, v) \in X\}$. We will show that $F_n \cong G_n$. We know that for some $(y, w) \in Y$ then $y \neq y'$ for all $(y', w') \in Y \backslash \{(y, w)\}$ since otherwise (V, Y) would not be a forest and X would not be a conflict-free set in F. So all edge set unions will only give a root y a new parent w once. So $\rho_{F_n}(y) = \rho_{F_n}(w)$ and $\rho_{G_n}(y) = \rho_{G_n}(w)$ hence y remains in the same tree in both F_n and G_n. Since this holds for all $(y, w) \in Y$ it follows that all elements in V remains in the same tree in both F_n and G_n. Hence $F_n \cong G_n$. $\square$

Algorithm 1.1 (Conflict-free Tree Union)**.** Let forest F be a tree and let $Z \subseteq V \times V$ be a set of pairs of elements in V that will be unioned in parallel. The conflict-free tree union algorithm is defined as:

$$\begin{array}{l}
\texttt{while } Z \neq \emptyset \texttt{ do} \\
\quad E := \pi_2(F) \\
\quad \text{pick conflict-free } X \subseteq Z \\
\quad \texttt{parfor } (u, v) \in X \texttt{ do} \\
\quad\quad E := E \cup \{(\rho_F(u), \rho_F(v))\} \\
\quad F := (V, E) \\
\quad Z := \{(u, v) : (u, v) \in Z \backslash X \land \rho_F(u) \neq \rho_F(v)\}
\end{array}$$

Algorithm 1.2 (Conflict-free Find)**.** Let forest $F = (V, E)$ be a forest, $(V, \leq)$ be a total ordering and $Z \subseteq V \times V$ be a set of pairs of elements in V.

Definition 1.13 (Union-Find Structure)**.** The union-find structure U is a forest $U = (V, E)$ where the vertices $V = S$ for some set of elements S. The edges $E \subseteq V \times V$ represent parent relations between elements in S such that $(u, v) \in E$ means that u has parent v.