1 Introduction

In this lecture, we will cover amortized analysis, which is a method where we consider the average work done over an entire sequence of operations instead of just considering the worst-case cost/time for a single operation; by doing such an analysis, we can obtain tighter bounds in scenarios when expensive operations occur rarely enough that we can charge their cost to more frequent inexpensive operations. We cover such charging arguments as well as the potential method which is another powerful tool for doing amortized analysis. We will apply both these techniques to binary counting, and the union-find data structure (which is needed to implement Kruskal’s algorithm efficiently).\footnote{Most materials are from a previous note by Nat Kell and Ang Li for this class in Fall 2014.}

2 Binary Counting

2.1 Amortized Analysis

Suppose we want to increment a variable $x$ starting at 0 until we reach some value $n$, where we represent $x$ as a binary number with $\lceil \log n \rceil + 1$ bits (we’ll denote this binary representation as $\text{BIN}(x)$). Using the basic carry addition algorithm (that we all know so well from primary school), we implement each $x++$ as follows. Starting at the least significant bit (LSB), if we observe a 1 we flip it to 0 and then move to the next bit to the left. Otherwise if we observe a 0, we flip it to a 1 and stop.

Over all $n$ increments, we can ask the question: how many bit flips do we do in total? Clearly, the number of flips for a single increment is $O(\log n)$ since there are only $\lceil \log n \rceil + 1$ bits, and since we do $n$ increments in total, a rough upper bound on the total flips is $O(n \log n)$. However, it seems like we should be able to tighten this aggregate bound since on many increments we are only flipping a few bits; ideally, we would like to show a bound of $O(n)$, which would establish that, even if the worst-case bound of a single increment is $\Theta(\log n)$, on average we are only doing a constant amount of work for each operation.

We can indeed obtain an $O(n)$ bound with the following “direct analysis.” Observe that the $k$th LSB (i.e., 0th least significant bit is the right most bit) can be flipped from 1 to 0 and back to 1 at most $n/2^k$ times. When this event happen, the counter has increased by $2^k$, and since our final total is $n$, it follows that these two flips can occur at most $n/2^k$ times. Summing over all bit positions $k$ and using the closed form for an infinity geometric series we obtain:

$$\text{Total bit flips} = \sum_{k=0}^{\lceil \log n \rceil + 1} \frac{n}{2^k} < n \cdot \sum_{k=0}^{\infty} \frac{1}{2^k} = 2n = O(n).$$
2.2 Charging Arguments

This analysis is similar to arguments we have seen previously this semester: For each possible index for a bit flip, we argued an upper bound on the number of times this type of flip-event can happen and summed these upper bounds over all possible positions to obtain the desired upper bound for the total number of flips. Now, we are going to perturb this analysis somewhat and instead frame it as a charging argument. The idea is that instead of analyzing each operation directly, we distribute or charge the work done on expensive operations onto inexpensive operation and then sum over all the work done over all operations with this new work distribution.

To make this more concrete, consider the following charging scheme for binary counting. The idea is that when a bit is set to 1 we charge 2 dollars, 1 is the actual cost of the setting and the other 1 is placed on the bit. Now every 1 in the counter has 1 dollar and we can charge nothing for the setting to 0 and just use the 1 dollar on the bit. First observe that:

1. On a given increment, there is exactly one 0-1 flip (the last flip we perform); therefore, there are exactly \(n\) 0-1 flips in total.
2. Each 1-0 flip is preceded by a unique 0-1 flip. (For each bit the flips alternate between 0-1 and 1-0)

By Observation 2, a given 0-1 flip is charged exactly once; thus now, we have distributed the work so that 1-0 flips cost nothing and 0-1 flips cost 2: one unit of work for doing the actual flip and another unit of work to charge the following 1-0 flip is now placed on the bit. (We have 1 unit on each bit with value 1 and will use it on the next flip of that bit.) Even though we have made 0-1 flips more expensive, we have only done so by a constant amount. By Observation 1, there are only \(n\) 0-1 flips in total, and therefore using this new work distribution we conclude that the number of flips is at most \(2n = O(n)\).

2.3 Potential Functions

Another method for doing amortized analysis is using what are called potential functions. Broadly defined, a potential function \(\Phi(i)\) maps the state of an algorithm or data structure after the \(i\)th operation to a carefully defined non-negative value. The naming convention of calling \(\Phi(i)\) a "potential" comes from the fact that the change in \(\Phi(i)\) is somewhat analogous to the state system accumulating potential energy and then releasing it later as kinetic energy. On an inexpensive operation \(i\), \(\Delta\Phi = \Phi(i) - \Phi(i - 1)\) will likely be positive and thus we build potential energy in the system. Then on expensive operations, we release potential energy as kinetic energy by making \(\Delta\Phi\) negative, which will counterbalance the higher cost. Another analogy that is often used is that the potential function is a bank account where we save money on inexpensive operations and spend the money we have saved on expensive operations.

More specifically, let \(c_i\) be the cost of operation \(i\) (so in the case of the binary counter, this is the number of bits flipped on the \(i\)th increment). Given a potential function \(\Phi\), we define the amortized cost \(\hat{c}_i\) of operation \(i\) to be \(c_i + \Phi(i) - \Phi(i - 1)\). Observe that we have the following bound if we perform \(n\) operations:

\[
\text{Total amortized cost} = \sum_{i=1}^{n} \hat{c}_i = \sum_{i=1}^{n} (c_i + \Phi(i) - \Phi(i - 1)) = \sum_{i=1}^{n} (c_i) + \Phi(n) - \Phi(0).
\] (1)

The last equality follows since all the \(\Phi(i)\) terms in the summation telescope except for \(\Phi(0)\) and \(\Phi(n)\) (i.e., for each \(j = 1, \ldots, n - 1\), the positive term \(\Phi(i)\) when \(i = j\) will cancel with the negative term \(-\Phi(i - 1)\) when \(i = j + 1\)). Therefore, as long as \(\Phi(0)\) and \(\Phi(n)\) are non-negative, then amortized cost is an upper bound on actual cost (since actual cost is just \(\sum_{i=1}^{n} c_i\)).
As we mentioned for our binary counter example, \( c_i \) is just the number of bit flips on the \( i \)th increment. To define our amortized cost, we will use the following potential function:

\[
\Phi(i) = \text{The number of 1s in } \text{BIN}(x) \text{ after } i \text{ increments.} \tag{2}
\]

To do our analysis, consider the difference between the number of 1s in \( x \) before and after the \( i \)th increment; namely, we will define \( \Phi(i) \) in terms of \( \Phi(i-1) \). Observe that based on the algorithm, there are \( c_i - 1 \) 1s that become 0s on the \( i \)th increment: the first \( c_i - 1 \) are 1s being flipped to 0, and then the last unit of cost is added from flipping the last 0 to a 1. Since this last flip also adds an extra 1 to \( x \), the total number of 1s after the \( i \)th increment is 

\[
\Phi(i) = \Phi(i-1) - (c_i - 1) + 1. 
\]

Therefore, the total amortized cost is as follows:

\[
\sum_{i=1}^{n} \hat{c}_i = \sum_{i=1}^{n} (c_i + \Phi(i) - \Phi(i-1)) \\
= \sum_{i=1}^{n} (c_i + \Phi(i-1) - (c_i - 1) + 1 - \Phi(i-1)) \quad \text{(since } \Phi(i) = \Phi(i-1) - (c_i - 1) + 1) \\
= \sum_{i=1}^{n} 2 = 2n. 
\]

Clearly, both \( \Phi(0) \) and \( \Phi(n) \) are non-negative (we cannot have a negative number 1s in \( \text{BIN}(x) \)); therefore by (1), \( 2n = O(n) \) is an upper bound on the total actual cost, as desired.

3 Revisiting Kruskal’s Algorithm: Union-Find Data Structure

3.1 Storing Components for Kruskal’s Algorithm

For a weighted graph \( G = (V,E) \) where \( w_e \) denotes the weight of edge \( e \in E \), recall Kruskal’s algorithm for computing a minimum spanning tree (MST) of \( G \) (if you are having trouble remembering the MST problem or Kruskal’s algorithm, you should go back and review the notes for Lecture 13). At a high level, we begin Kruskal’s algorithm by initializing each vertex to be in its own component and the set of selected edges to be empty set. Then in order of increasing edge weight, we repeatedly add edges to the set of selected edges if they merge two of the current components together (i.e., if \( e = (u,v) \) is the edge we are considering, we add edge \( e \) to the selected edges if \( u \) is currently in a different component than \( v \)). Once all vertices lie in the same component, we argued that the resulting structure does in fact give us a MST.

However, when we previously outlined the pseudo-code for Kruskal’s, we glossed over how to represent these collections of vertex sets in memory. On the iteration where we consider adding edge \( e = (u,v) \), we need to quickly find out if \( u \) and \( v \) belong to the same component, and if they do not, we need to merge these components together.

To perform such queries and operations, we will implement a union-find data structure. A union-find data structure \( D \) is defined over a set of \( n \) elements \( U = \{x_1, \ldots, x_n\} \) and maintains a collection of disjoint subsets \( S_1, \ldots, S_h \) to which these elements belong, where \( 1 \leq h \leq n \). As in our scenario above, every element is in its own subset when \( D \) is initialized. \( D \) then supports the following two operations:

- \( \text{FIND}(x) \): return \( S_i \) such that \( x \in S_i \) (in an actual implementation, we would likely just return the representative element for set \( S_i \)).
- \( \text{UNION}(S_i,S_j) \): Replace \( S_i \) and \( S_j \) with \( S_i \cup S_j \) in the set system.
So for Kruskal’s algorithm, we initialize a union-find data structure over the vertices. For each edge \( e = (u, v) \), if \( \text{FIND}(u) \neq \text{FIND}(v) \), then we call \( \text{UNION}(\text{FIND}(u), \text{FIND}(v)) \) to merge \( u \) and \( v \)’s components (otherwise, we move on to the next edge). In total we will issue at most \( 2m \) \( \text{FIND} \) queries and always perform \( n \) \( \text{UNION} \) operations.

### 3.2 Implementing Union-Find

We now turn to the details of implementing \( \text{FIND}(x) \) and \( \text{UNION}(S_i, S_j) \) efficiently. Our first implementation decision is to how to represent the “labels” for each set. Here, we will use elements as representatives: At any given time, there will be a unique \( x \in S_i \) which we will return as the label of \( S_i \) whenever we call \( \text{FIND}(y) \) for any \( y \in S_i \) (in the following implementations, we will make it clear how each representative is determined/maintained).

#### 3.2.1 Union-Find with Linked Lists

The most obvious way to represent the set system is to just use a collection of linked lists. For each set \( S_i \), we have a corresponding linked list \( L_i \) which contains the elements in \( S_i \). The representative of \( L_i \) will just be element at the head of the list, which is then preceded by the rest elements in \( S_i \) through a sequence of pointers. To execute \( \text{FIND}(x) \), we start at \( x \) and follow the path of pointers leading to the head and then return it as the label of the set. Note that since there can be \( \Omega(n) \) elements in a set, we might have to traverse \( \Omega(n) \) links to reach a set’s label; therefore when using list, \( \text{FIND}(x) \) runs in \( \Theta(n) \) time in the worst case. \( \text{UNION} \) operations, however, are quite simple. To implement \( \text{UNION}(S_i, S_j) \), we just make the head of \( L_i \) point to the tail of \( L_j \) (or vice versa). Since we can store head/tail metadata along with the head of a list, \( \text{UNION} \) is an \( O(1) \) time operation.

As noted above, a given run of Kruskal’s may do \( 2m \) \( \text{FIND}(e) \) queries, which gives us a \( \Theta(mn) \) time algorithm in the worst case. When we first presented Kruskal’s algorithm, we claimed a running time of \( O(m \log n) \); therefore, using this linked list implementation will not suffice.

#### 3.2.2 Union-Find with Trees

If we want to maintain the property that \( \text{UNION} \) operations still take \( O(1) \) time, a natural improvement to this linked list scheme is to instead maintain a set of trees. Now, a set \( S_i \) corresponds to a tree \( T_i \), where the representative of the set is at the root. To implement \( \text{UNION}(S_i, S_j) \), we make \( T_i \) a subtree of \( T_j \) by making the root of \( T_j \) the parent of the root of \( T_i \). Note that this implies that each tree is not necessarily binary since a fixed root \( r \) can participate in several \( \text{UNION} \) operations (it is possible that each \( \text{UNION} \) results in another subtree rooted at \( r \)).

\( \text{FIND}(x) \) still works in the exact same way—we simply start at \( x \) and follow a path up the corresponding tree via parent pointers until we reach the root. Our hope is that if each tree structure remains balanced, then we can bound the longest path from node to root when doing a \( \text{FIND} \) query. However, our current
specifications do not ensure balance. For example, consider the sequence of \( n \) unions

\[
\{x_1\} \cup \{x_2\} \\
\{x_3\} \cup \{x_1,x_2\} \\
\{x_4\} \cup \{x_1,x_2,x_3\} \\
\vdots \\
\{x_n\} \cup \{x_1,\ldots,x_{n-1}\}.
\]

Informally, we grow one particular set in the set system, and then with each \textsc{Union} we add one of the remaining singleton sets to this growing set. When we perform \textsc{Union}(\( S_i, S_j \)) in this scheme, note that we are arbitrarily picking which root (the root of \( T_i \) or the root \( T_j \)) becomes the new root when we combine \( T_i \) and \( T_j \). Thus in the above example, it is possible that when we merge \( S = \{x_i\} \) with \( S' = \{x_1,\ldots,x_{i-1}\} \), we use \( x_i \) as the new root each time. If we are unfortunate enough to have this sequence of events happen for each union, then the resulting tree structure will just be an \( n \) element linked list (and therefore it is still possible for \textsc{Find}(\( x \)) to take \( \Omega(n) \) time).

A straightforward way to fix this pitfall is to do what is called \textit{union-by-depth}. For each tree \( T_i \), we keep track of its depth \( d_i \), or the longest path from the root to any node in the tree. Now when we perform a \textsc{Union}, we check to see which tree has the larger depth and then use the root of this tree as the new root. Note that this extra information can be easily stored and updated with the root of each tree: If we call \textsc{Union}(\( S_i, S_j \)) and \( d_i \leq d_j \), then the root of \( T_j \) becomes the root of \( T_i \cup T_j \), and we update the depth of \( T_i \cup T_j \) to be \( \max(d_j,d_i+1) \) (note this max is only necessary in the case where \( d_i = d_j \)—otherwise, the depth of the combined tree is no larger than depth of \( T_j \)).

What does “union-by-depth” buy us? The following theorem establishes that this feature does indeed balance the trees in the set system.

\textbf{Theorem 1.} For a tree implementation of the union-find data structure that uses union-by-depth, any tree \( T \) (representing set \( S_i \) in the set system) with depth \( d \) contains at least \( 2^d \) elements.

\textbf{Proof.} We do a proof by induction on the tree depth \( d \). Since a tree \( T \) with depth 0 has has \( 2^0 = 1 \) elements, the base case is trivial. For the inductive step, assume that the hypothesis holds for all trees with depth \( k-1 \), i.e., any tree with depth \( k-1 \) contains at least \( 2^{k-1} \) nodes. Observe that in order to build a tree \( T \) with depth \( k \), we must merge together two trees \( T_i \) and \( T_j \) that both have depth \( k-1 \); otherwise, we would either have:

1. Both \( T_i \) and \( T_j \) have depth strictly less than \( k-1 \). Since the depth of \( T_i \cup T_j \) can be no more \( \max(d_i,d_j) + 1 \), the combined tree \( T_i \cup T_j \) can have depth at most \( k-1 \) (note this is true regardless of whether we use union-by-depth).

2. Exactly one tree has depth \( k-1 \); without loss of generality, suppose \( d_j = k-1 \) and \( d_i < k-1 \). Since we are using union-by-depth, we will make the root of \( T_i \cup T_j \) the root of \( T_j \). Since \( d_i < k-1 \), the length of any path from this new root of to any node in \( T_i \) can be at most \( k-1 \). Since \( T_j \) has depth \( k-1 \) and no node in within this subtree changes depth in \( T_i \cup T_j \), the depth of the combined tree is exactly \( k-1 \).

Therefore, assume \( d_i = d_j = k-1 \); we can then apply our inductive hypothesis to both \( T_i \) and \( T_j \) to obtain:

\[
|T| = |T_i \cup T_j| = |T_i| + |T_j| \geq 2^{k-1} + 2^{k-1} = 2^k,
\]

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Theorem 1 implies that any tree with $n$ elements can have depth at most $\log n$ (the theorem implies $n \geq 2^d$ where $d$ is the depth of the largest tree/subset, implying $\log n \geq d$). Therefore, $\text{FIND}(x)$ runs in $O(\log n)$ when using union-by-depth. From Kruskal’s perspective, this gives us the desired running time. The initial sort we do on the edge weights takes $O(m \log m) = O(m \log n^2) = O(m \log n)$ time. We then do $n$ UNIONS that each take $O(1)$ time and $2m$ FINDs that each take $O(\log n)$ time. Therefore, the overall running time of Kruskal’s using this implementation is $O(m \log n) + O(n) + O(m \log n) = O(m \log n)$.

3.2.3 Union-Find with Stars

Although doing a tree implementation that uses union-by-depth gave us the desired asymptotic running time of $O(m \log n)$, it is a bit unsettling that UNIONS take constant time and FINDs could take $\Omega(\log n)$ time. Since $n = O(m)$ for any graph where we want to find a spanning tree, it seems a bit wasteful that our implementation gives us a faster running time for the function we call fewer times (recall we perform $n$ UNIONS and at most $2m$ FINDs). Therefore in this section, we will look at an implementation where we force each FIND to take $O(1)$ time, but as a result make UNIONS operations more expensive (but hopefully by not too much).

The most naive way to achieve $O(1)$-time FINDs is to represent sets as star graphs. A star graph is simply a tree with a designated a center node such that every other node in the graph is a leaf that is only adjacent (or points) to this center node. Thus, we will maintain that each tree $T_i$ that represents a set $S_i$ is a star graph, where the center node of $T_i$ is the representative of $S_i$. Clearly with this scheme, when we call $\text{FIND}(x)$ we must only traverse at most 1 link to reach the representative node, and therefore the running time of $\text{FIND}(x)$ is $O(1)$.

However to maintain this star graph structure, we will need to take more time when we make a UNION call. If we have two star graphs $T_i$ and $T_j$ that we want to merge, we first need to pick which representative element we will use for $T_i \cup T_j$ (just like for our previous implementation with balanced trees). If we pick $T_j$’s center $c_i$ to be the new center, we then need to iterate through every element $x \in T_j$ and make $x$ point to $c_i$. Since $T_j$ could have $\Omega(n)$ elements, this operation could take $\Omega(n)$ time. Therefore if we do $n$ UNION operations, our running time for Kruskal’s is now $\Theta(n^2)$ (which could be worse than $O(m \log n)$).

To avoid this problem, we will use a rule that is similar to union-by-depth. Namely, we will use union-by-size. Namely, if we are given two star graphs $T_j$ and $T_i$, we will dissemble the smaller of the two sets and make these elements point to the center of the larger set (and leave the star graph in the larger graph untouched).

To analyze the speedup obtained from doing union-by-size, we use a charging argument to do an amortized analysis over the $n$ UNIONS performed by Kruskal’s. We use the following charging scheme: Any time we merge two trees $T_i$ and $T_j$ such that $|T_i| \leq |T_j|$, we will simply put a unit of charge on each element in $T_j$ (remember that we are taking the elements of $T_j$ and changing their pointers to the center of $T_i$). Note that for all $x \in T_i$, $x$ now belongs to a set that is twice as large. We also know that for $x \in U$, the set to which $x$ belongs can double at most $\log n$ times (the size of final merged set is $n$); therefore, the charge on a given element $x$ can be at most $\log n$ after $n$ unions. Since the total time needed over all $n$ unions is equal to the total charge distributed over the elements, the time it takes to make $n$ UNION calls is $O(n \log n)$. Note that even though Kruskal’s algorithm still runs in $O(m \log n)$ time since we must initially sort the edges, we have reduced the time it takes to execute Kruskal’s merging procedure to $O(n \log n + m)$. 

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3.2.4 Optimal Union-Finds: Path Compression and Union-by-Rank

We will now outline the best scheme for implementing a union-find data structure. This implementation will be more akin to what we saw in Section 3.2.2 when we used balanced trees to represent our set system. The main feature we will add to this implementation is what is known as path compression, which will attempt to make our trees more “star-graph-like” whenever we make a FIND call (so in some sense, we are combining the strategies in sections 3.2.2 and 3.2.3).

More specifically, whenever we call FIND(x) where x ∈ Si, we will follow some path P from x to the root ri of Si. For each element y ∈ P, we now know that y belongs to set Si; therefore at this point, it makes sense to make each of these elements point directly to ri. FIND(x) with path compression does exactly this modification, and therefore after the procedure completes, ri and all the elements along P now form a star graph in Ti. Note that it is not too hard to implement FIND(x) such that it returns ri, makes every element in P point directly to ri, and runs in O(|P|) time.

To implement UNION, we essentially still use union-by-depth. We still merge components using the same rule (we make the tree with the smaller depth a subtree of the tree with the larger depth). Note, however, that because we might have path compressing FIND calls in-between UNION calls, we might compress a path that defined the depth a given tree Ti. In such a case, di no longer accurately stores the depth of di.

How does one fix this issue? The answer is that we do not. Instead, we just call this di the rank of Ti and use it in the same way we would in our union-by-depth scheme. It turns out that using these two features in combination gives us an extremely good bound. We define

\[
\log^* n = 1 + \log^* (\log n) \quad (n \geq 2), \quad \text{and} \quad \log^* 1 = 0
\]

We categorize the ranks into groups by the value of \( \log^* n \):

<table>
<thead>
<tr>
<th>ranks</th>
<th>( \log^* n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>{1}</td>
<td>0</td>
</tr>
<tr>
<td>{2}</td>
<td>1</td>
</tr>
<tr>
<td>{3,4}</td>
<td>2</td>
</tr>
<tr>
<td>{5,6,...,16}</td>
<td>3</td>
</tr>
<tr>
<td>{17,18,...,2^{16}}</td>
<td>4</td>
</tr>
<tr>
<td>{65537, 65538,...,2^{65536}}</td>
<td>5</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

We give \( 2^k \) dollars to a node whose rank is in \( \{k+1, k+2, \ldots, 2^k\} \) and there are at most \( \frac{n}{2^k} \) nodes whose rank is in that group, therefore we give at most \( O(n) \) dollars totally to a group. There are \( O(\log^* n) \) groups and we totally give \( O(n \log^* n) \) dollars.