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Amortized Analysis

The basic idea of amortization is simple: you have a process where some operations are expensive, some others are cheap. You want to show that there is some α such that over any sequence of T operations, you pay at most $T \cdot \alpha$ for some value α . Then you say the amortized (or average) cost per operation is at most α .

2.1 The Binary Counter

You have a binary counter that starts off with all zeroes. Each time the counter increments by 1. So the first few settings are:

The cost of an increment is the number of bits that change. So the first few increments cost

$$1, 2, 1, 3, 1, 2, 1, 4, 1, 2, 1, 3, 1, 2, 1, 5, \dots$$

What is the amortized cost over T operations? There are many ways to solve this:

2.1.1 Brute Force

First imagine that T is a power of 2, say 2^t . Then observe that the first 2^{t-1} costs look the same as the last 2^{t-1} , except for the very last operation costing one more. So if the sum of the first 2^t costs is S_t , we get

$$S_t = 2S_{t-1} + 1.$$

And $S_0 = 1$. Solving this gives $S_t = 2^{t+1} - 1$. And hence the amortized cost (per operation) is

$$\frac{2^{t+1} - 1}{2^t} \leq 2.$$

Then one can argue that if T is not a power of 2, then break the process into prefixes of length that are powers of 2, etc. But all this requires some work. Let's see other approaches.

2.1.2 *Summing More Smartly*

Observe that the lowest order bit changes each step. The second lowest-order bit changes once every other step. The third one changes once every fourth step. So the number of changes in T steps is at most

$$T + \lceil T/2 \rceil + \lceil T/4 \rceil + \dots \leq 2T.$$

And hence the amortized cost per operation is at most 2.

2.1.3 *The Banker's Method*

Let's maintain the invariant that each 1 has a dollar bill sitting next to it, that can pay for changing it back to zero. This is vacuously satisfied at the start: we start with all zeros, so there are no 1s. Now each increment consists of changing some suffix of 1s to zeros, followed by changing a single zero to a 1. All the $1 \rightarrow 0$ transitions are paid for by the dollar bills, so we only need to pay for the single $0 \rightarrow 1$ transition, and to put down the dollar bill on it. Hence we pay \$2 per operation.

We call this the *banker's method*: we show that for each operation we pay \$ α , some of which is used to pay for the current operation and some to save for later, more expensive operations. You can think of this as keeping a bank account, and saving the extra amount from the cheaper operations to use for the expensive operations.

2.2 *The Potential Function Method*

Let us present a more general framework in which most amortized analyses can be placed. At each time, the system is supposed to be in some state, drawn from a collection Ω of states. We maintain a function $\Phi : \Omega \rightarrow \mathbb{R}$ called the *potential function*. With an operation at time t the system moves from some state s_{t-1} to some other state s_t . This changes the potential of the state from $\Phi(s_{t-1})$ to $\Phi(s_t)$. Suppose the operation costs c_t . Then the *amortized cost* at time t is defined as:

$$A_t := c_t + (\Phi(s_t) - \Phi(s_{t-1})). \quad (2.1)$$

If we sum this over all times, the telescoping sum gives

$$\sum_{t=1}^T A_t = \sum_{t=1}^T c_t + \Phi(s_T) - \Phi(s_0).$$

Now suppose we can show the following three things:

1. The potential starts at zero (i.e., $\Phi(s_0) = 0$),
2. it is non-negative, so that $\Phi(s_T) \geq 0$, and
3. $A_t \leq \alpha$ for all times t .

Then we get

$$T\alpha \geq \sum_{t=1}^T A_t = \sum_{t=1}^T c_t + (\geq 0 - 0).$$

In other words, the total cost is at most $T\alpha$, and hence the amortized cost is at most α .

This all sounds very abstract: I like to think of $\Phi(s)$ as being the bank account when you get to state s . The expression on the right of (2.1) is the actual cost of the operation, plus the change in the bank account. That is what we have to pay per operation. So sometimes the operations are cheap but the bank account goes up, and we need to pay for this increase. At other times, the operations are expensive, and then the bank account goes down, with this decrease helping to pay this larger cost (and us paying only the difference).

For example: if the current number in the binary counter is s , then define

$$\Phi(s) = \text{number of 1s in the binary representation of } s.$$

Now if we changing from s to $s + 1$ requires us to flip f bits, $f - 1$ of these flips must be $1 \rightarrow 0$, and the last one is $0 \rightarrow 1$. So the number of 1s decreases by $f - 2$. This means the amortized cost at each timestep is

$$A_{s \rightarrow s+1} = f - (f - 2) = 2.$$

Observe that the potential here matches the total money in the bank from the previous analysis.

2.2.1 Why and How

You may ask: why even talk about potential functions, why not just use the banker's method all the time? The answer is that potentials are a more general idea, and sometimes they will be more useful. We will see some later in the course.

And the next natural question: how do you come up with a potential function? This is more difficult, there is no silver bullet. The only suggestion is to look closely what the algorithm

2.3 The List-Based Union-Find Data Structure

Recall that the operations are:

1. $\text{Makeset}(e)$: create a singleton set $\{e\}$, costs 1.
2. $\text{Find}(e)$: return the name of the set containing e , costs 1.
3. $\text{Union}(e, f)$: merges the sets A, B containing e, f , costs $\min(|A|, |B|)$.

The question is: if you have n Makesets, m Finds and u Unions, what is the total cost?

Theorem 2.1. *The total cost is at most $m + O(n \log n)$.*

Here are two proofs:

1. Using the banker's method: each $\text{Makeset}(e)$ brings $\log_2 n$ dollars with it, which is stored with the element e . Each time e belongs to the smaller set involved in a Union , it pays for this operation. But the size of the set containing e at least doubles, so e has to pay at most $\log_2 n$ times.
2. Using potentials: if the sets at the current state s have size n_1, \dots, n_k , let

$$\Phi(s) = \sum_i n_i \log_2(n/n_i).$$

Each makeset costs $\log_2 n$, the finds cost 1. And when we replace sets of size $n_i \leq n_j$ by a new set of size $n_i + n_j$, the amortized cost for each union is

$$\begin{aligned} & n_i + (n_i + n_j) \log_2 \frac{n}{n_i + n_j} - n_i \log_2 \frac{n}{n_i} - n_j \log_2 \frac{n}{n_j} \\ &= n_i - \underbrace{n_i \log_2 \frac{n_i + n_j}{n_i}}_{\geq 1} - \underbrace{n_j \log_2 \frac{n_i + n_j}{n_j}}_{\geq 0} \\ &\leq 0. \end{aligned}$$

Hence, the total cost is $O(m + n \log n)$.

One can improve both the analyses above a bit further to $O(m + n + u \log n)$: each union brings in $\log_2 n$ dollars, with the first union involving element e giving its $\log_2 n$ dollars to e .