1 Example

Exercise. Suppose T(1) = 3 and T(n) = 3T(n/2) + n. How would you find T(8)? The point of this exercise is the process.

Solution.

Expand and substitute using the formula for the recurrence:

$$T(8) = 3T(4) + 8$$

= 3 [3T(2) + 4] + 8 = 9T(2) + 20
= 9 [3T(1) + 2] + 20 = 27T(1) + 38 = 119

This is the same approach that's used to prove the Master Theorem.

2 Master Theorem

Start with a recurrence $T(n) = aT(n/b) + cn^k$ (supposing that $T(p_0) = q_0$ for constants p_0 and q_0) and expand:

$$T(n) = aT(n/b) + cn^{k}$$

$$= a \left[aT(n/b^{2}) + c \left(\frac{n}{b}\right)^{k} \right] + cn^{k} = a^{2}T(n/b^{2}) + cn^{k} \left(1 + \frac{a}{b^{k}}\right)^{k}$$

$$\vdots$$

$$= a^{s}T(n/b^{s}) + cn^{k} \left[\left(\frac{a}{b^{k}}\right)^{s} + \left(\frac{a}{b^{k}}\right)^{s-1} + \dots + \frac{a}{b^{k}} + 1 \right]$$

We stop expanding when we reach the base case, when $\frac{n}{b^s} = p_0$. This occurs after $s \approx \log_b \left(\frac{n}{p_0}\right) = \log_b n + \text{constant iterations.}$ Notice that the expression is split into two terms. The asymptotic form of T(n) is just a competition between these two terms to see which one dominates.

The second term has a geometric sum: using the formula for a geometric sum gives:

$$T(n) = a^{s}q_{0} + cn^{k} \left[\frac{1 - \left(\frac{a}{b^{k}}\right)^{s+1}}{1 - \frac{a}{b^{k}}} \right]$$

Exercise. Use the above expansion to derive the case of the Master Theorem for $a < b^k$.

Solution.

Here, $\frac{a}{b^k} < 1$, and as n (and therefore s) grows large the sum of the above geometric series is dominated by the constant term $\frac{1}{1-\frac{a}{b^k}} = \Theta(1)$. So $T(n) = \Theta(a^s) + \Theta(n^k)$. Using our expression for s:

$$a^{s} = \Theta(a^{\log_{b} n}) = \Theta(n^{\log_{b} a}) = o(n^{k})$$

since $a < b^k$ means that $\log_b a < k$. We therefore get that $T(n) = o(n^k) + \Theta(n^k) = \Theta(n^k)$.

Exercise. Now derive the Master Theorem for $a > b^k$.

Solution.

Proceeding like the previous case, the geometric sum is now dominated by the:

$$\frac{\left(\frac{a}{b^k}\right)^{s+1}}{\frac{a}{b^k} - 1} = \Theta\left(\left(\frac{a}{b^k}\right)^s\right)$$

term. Then the second term of T(n) is:

$$cn^k \cdot \Theta\left(\left(\frac{a}{b^k}\right)^{\log_b n}\right) = cn^k \cdot \Theta\left(\frac{n^{\log_b a}}{n^k}\right) = \Theta\left(n^{\log_b a}\right)$$

This along with the result from the previous exercise that $a^s = \Theta(n^{\log_b a})$ gives that $T(n) = \Theta(n^{\log_b a})$.

Exercise. Derive the Master Theorem for $a = b^k$.

Solution.

Every term in the geometric series is now 1. There are s + 1 terms, so the second term of T(n) becomes:

$$cn^{k}(s+1) = \Theta\left(n^{k}\log_{b}n\right) = \Theta\left(n^{k}\log n\right)$$

The first term of T(n) is $\Theta\left(n^{\log_b a}\right) = \Theta\left(n^k\right)$ so the second term dominates and $T(n) = \Theta\left(n^k \log n\right)$.

Qualitatively, if $a > b^k$, the bottleneck of the recurrence is the number of recursive calls we have to make. Otherwise, it's the extra work done *during* each call (i.e. the cn^k term) that dominates the runtime.