In lecture, we described an algorithm of Karatsuba that multiplies two n-digit integers using $O(n^{\lg 3})$ single-digit additions, subtractions, and multiplications. In this lab we'll look at some extensions and applications of this algorithm.

1. Describe an algorithm to compute the product of an n-digit number and an m-digit number, where $m < n$, in $O(m^{\lg 3-1}n)$ time.

Solution: Split the larger number into $\lceil n/m \rceil$ chunks, each with m digits. Multiply the smaller number by each chunk in $O(m^{\lg 3})$ time using Karatsuba's algorithm, and then add the resulting partial products with appropriate shifts.

```
SkewMultiply(x[0..m-1], y[0..n-1]):
  prod ← 0
  for i ← 0 to ⌈n/m⌉ − 1
      chunk ← y[i·m .. (i+1)·m − 1]
      prod ← prod + Multiply(x, chunk) · 10^(i·m)
  return prod
```

Each call to Multiply requires $O(m^{\lg 3})$ time, and all other work within a single iteration of the main loop requires $O(m)$ time. Thus, the overall running time of the algorithm is $O(1) + \lceil n/m \rceil O(m^{\lg 3}) = O(m^{\lg 3-1}n)$ as required.

This is the standard method for multiplying a large integer by a single "digit" integer ***written in base*** $\mathbf{10^m}$, but with each single-"digit" multiplication implemented using Karatsuba's algorithm. ■

2. Describe an algorithm to compute the decimal representation of 2^n in $O(n^{\lg 3})$ time. (The standard algorithm that computes one digit at a time requires $\Theta(n^2)$ time.)

Solution: We compute 2^n via repeated squaring, implementing the following recurrence:

$$2^n = \begin{cases} 1 & \text{if } n = 0 \\ (2^{n/2})^2 & \text{if } n > 0 \text{ is even} \\ 2 \cdot (2^{\lfloor n/2 \rfloor})^2 & \text{if } n \text{ is odd} \end{cases}$$

We use Karatsuba's algorithm to implement decimal multiplication for each square.

```
TwoToThe(n):
  if n = 0
      return 1
  m ← ⌊n/2⌋
  z ← TwoToThe(m)      ⟨⟨recurse!⟩⟩
  z ← Multiply(z, z)   ⟨⟨Karatsuba⟩⟩
  if n is odd
      z ← Add(z, z)
  return z
```

The running time of this algorithm satisfies the recurrence $T(n) = T(\lfloor n/2 \rfloor) + O(n^{\lg 3})$. We can safely ignore the floor in the recursive argument. The recursion tree for this algorithm is just a path; the work done at recursion depth i is $O((n/2^i)^{\lg 3}) = O(n^{\lg 3}/3^i)$. Thus, the levels sums form a descending geometric series, which is dominated by the work at level 0, so the total running time is at most $O(n^{\lg 3})$. ■

3. Describe a divide-and-conquer algorithm to compute the decimal representation of an arbitrary n-bit binary number in $O(n^{\lg 3})$ time. *[Hint: Let $x = a \cdot 2^{n/2} + b$. Watch out for an extra log factor in the running time.]*

Solution: Following the hint, we break the input x into two smaller numbers $x = a \cdot 2^{n/2} + b$; recursively convert a and b into decimal; convert $2^{n/2}$ into decimal using the solution to problem 2; multiply a and $2^{n/2}$ using Karatsuba's algorithm; and finally add the product to b to get the final result.

```
DECIMAL(x[0..n-1]):
  if n < 100
      use brute force
  m ← ⌈n/2⌉
  a ← x[m..n-1]
  b ← x[0..m-1]
  return ADD(MULTIPLY(DECIMAL(a), TWOTOTHE(m)), DECIMAL(b))
```

The running time of this algorithm satisfies the recurrence $T(n) = 2T(n/2) + O(n^{\lg 3})$; the $O(n^{\lg 3})$ term includes the running times of both MULTIPLY and TWOTOTHE (as well as the final linear-time addition).

The recursion tree for this algorithm is a binary tree, with 2^i nodes at recursion depth i. Each recursive call at depth i converts an $n/2^i$-bit binary number to decimal; the non-recursive work at the corresponding node of the recursion tree is $O((n/2^i)^{\lg 3}) = O(n^{\lg 3}/3^i)$. Thus, the total work at depth i is $2^i \cdot O(n^{\lg 3}/3^i) = O(n^{\lg 3}/(3/2)^i)$. The level sums define a descending geometric series, which is dominated by its largest term $O(n^{\lg 3})$.

Notice that if we had converted $2^{n/2}$ to decimal *recursively* instead of calling TWOTOTHE, the recurrence would have been $T(n) = 3T(n/2) + O(n^{\lg 3})$. Every level of this recursion tree has the same sum, so the overall running time would be $O(n^{\lg 3} \log n)$. ■

Other Divide and Conquer Problems:

4. Given an arbitrary array $A[1..n]$, describe an algorithm to determine in $O(n)$ time whether A contains more than $n/4$ copies of any value. **Do not use hashing, or radix sort, or any other method that depends on the precise input values.**

Solution: The algorithm is formally described below. We use the fact that the selection problem can be solved in linear time. That is, given an unsorted array A of n values and an index j between 1 and n, we can find the j-th ranked element in A in $O(n)$ time. We denote this black box algorithm as SELECT(A[1..N], j) which returns the value of the j-th ranked element in A. To determine whether an element appears more than $n/4$ times, we select values with rank $n/4$, $2n/4$, and $3n/4$. If an element x appears more than $n/4$ times, it follows that at least one of these selected values is equal to x. Thus, we can scan and count the number of occurrences of each of these selected values.

```
Contains4Duplicates(A[1..N])
    x_1 ← SELECT(A, ⌈N/4⌉)
    x_2 ← SELECT(A, ⌈2N/4⌉)
    x_3 ← SELECT(A, ⌈3N/4⌉)
    for (i ← 1 : 3)
        count ← 0 for (j ← 1 : N)
            if (A[j] = x_i) then count++1
        if (count > N/4) then return True
    return False
```

Since SELECT runs in $O(n)$ time, finding x_1, x_2, and x_3 also takes $O(n)$ time. Looping over the array of length n a total of 3 times takes $O(n)$ time. Thus, this algorithm runs in the required $O(n)$ time.

To prove correctness of the algorithm, we must show that if an element appears more than $n/4$ times, it must be at least one of the selected values with rank $\lceil n/4 \rceil$, $\lceil 2n/4 \rceil$, or $\lceil 3n/4 \rceil$. Assume an element x appears $i > n/4$ times. Then, there must be consecutive ranks $j, ..., j+i-1$ with value x. Without loss of generality, consider the number of values of rank between $\lceil n/4 \rceil$ and $\lceil 2n/4 \rceil$ (excluding the outside values). Since $\lceil n/4 \rceil \geq n/4$ and $\lceil 2n/4 \rceil \leq 2n/4+1$, the maximum number of values is given by $(2n/4+1)-(n/4)-1 = n/4$. Thus, there are at most only $n/4$ spots for more than $n/4$ values. By pigeonhole principle, one of the selected values must be equal to x. ■

Think about later:

5. Suppose we can multiply two n-digit numbers in $O(M(n))$ time. Describe an algorithm to compute the decimal representation of an arbitrary n-bit binary number in $O(M(n)\log n)$ time.

Solution: We modify the solutions of problems 2 and 3 to use the faster multiplication algorithm instead of Karatsuba's algorithm. Let $T_2(n)$ and $T_3(n)$ denote the running times of TwoToThe and Decimal, respectively. We need to solve the recurrences

$$T_2(n) = T_2(n/2) + O(M(n)) \quad \text{and} \quad T_3(n) = 2T_3(n/2) + T_2(n) + O(M(n)).$$

But how can we do that when we don't know $M(n)$?

For the moment, suppose $M(n) = O(n^c)$ for some constant $c > 0$. Since any algorithm to multiply two n-digit numbers must *read* all n digits, we have $M(n) = \Omega(n)$, and therefore $c \geq 1$. On the other hand, the grade-school lattice algorithm implies $M(n) = O(n^2)$, so we can safely assume $c \leq 2$. With this assumption, the recursion tree method implies

$$T_2(n) = T_2(n/2) + O(n^c) \implies T_2(n) = O(n^c)$$

$$T_3(n) = 2T_3(n/2) + O(n^c) \implies T_3(n) = \begin{cases} O(n\log n) & \text{if } c = 1, \\ O(n^c) & \text{if } c > 1. \end{cases}$$

So in this case, we have $T_3(n) = O(M(n)\log n)$ as required.

In reality, $M(n)$ may not be a simple polynomial, but we can effectively ***ignore*** any sub-polynomial noise using the following trick. Suppose we can write $M(n) = n^c \cdot \mu(n)$ for some constant c and some arbitrary non-decreasing function $\mu(n)$.[a]

To solve the recurrence $T_2(n) = T_2(n/2) + O(M(n))$, we define a new function $\tilde{T}_2(n) = T_2(n)/\mu(n)$. Then we have

$$\tilde{T}_2(n) = \frac{T_2(n/2)}{\mu(n)} + \frac{O(M(n))}{\mu(n)} \leq \frac{T_2(n/2)}{\mu(n/2)} + \frac{O(M(n))}{\mu(n)} = \tilde{T}_2(n/2) + O(n^c).$$

Here we used the inequality $\mu(n) \geq \mu(n/2)$; this the only fact about μ that we actually need. The recursion tree method implies $\tilde{T}_2(n) \leq O(n^c)$, and therefore $T_2(n) \leq O(n^c) \cdot \mu(n) = O(M(n))$.

Similarly, to solve the recurrence $T_3(n) = 2T_3(n/2) + O(M(n))$, we define $\tilde{T}_3(n) = T_3(n)/\mu(n)$, which gives us the recurrence $\tilde{T}_3(n) \leq 2\tilde{T}_3(n/2) + O(n^c)$. The recursion tree method implies

$$\tilde{T}_3(n) \leq \begin{cases} O(n\log n) & \text{if } c = 1, \\ O(n^c) & \text{if } c > 1. \end{cases}$$

In both cases, we have $\tilde{T}_3(n) = O(n^c \log n)$, which implies that $T_3(n) = O(M(n)\log n)$. ■

[a] A recent multiplication algorithm based on fast Fourier transforms runs in $O(n \log n\, 2^{O(\log^* n)})$ time, so we can safely assume that $c = 1$. But our solution doesn't use that fact.