

June 16, 2016

## 1 Multiplying Large Numbers

Given 2  $n$ -bit numbers  $A$  and  $B$ , compute  $AB$ . Trivially there's a lower bound of  $\Omega(N)$ . Trivial solution is  $O(N^2)$ .

Alternatively, use Karatsuba-Ofman's Algorithm: see [https://en.wikipedia.org/wiki/Karatsuba\\_algorithm](https://en.wikipedia.org/wiki/Karatsuba_algorithm)

If  $x = x_1B^m + x_2$ ,  $y = y_1B^m + y_2$ , then we exploit the fact that  $z = x_1y_2 + x_2y_1 = (x_1 + y_1)(x_2 + y_2) - x_1y_1 - x_2y_2$  and  $xy = (x_1B^m + x_2)(y_1B^m + y_2) = x_1y_1B^{2m} + zB^m + x_2y_2$ .

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In [134]: # O(N ^ 2)
          # a,b are lists of {0, 1}
          def multiply_1(a, b):
              assert len(a) <= len(b)
              if len(a) <= 0:
                  return []
              elif len(a) == 1:
                  if a[0] == 0:
                      return [0 for i in b]
                  else:
                      return b[:]
              right = multiply(a[:len(a)/2], b) + [0 for _ in range(len(a)/2, len(a))
              left = [0 for _ in range(len(a)/2)] + multiply(a[len(a)/2:], b)
              s = [l+r for l,r in zip(left, right)] # contains 2's and possibly 3

              for i in reversed(range(len(s))):
                  if s[i] == 2 or s[i] == 3:
                      s[i] = 0 if s[i] == 2 else 1
                      if i == 0:
                          s.insert(0, 1)
                      else:
                          s[i-1] += 1
              return s[s.index(1):] # filters out 0-padding

          # Karatsuba
          # Analysis: T(n) = 3 T(n/2) + Theta(n)
          # via master theorem: O(n ^ log_2(3))
          def multiply_2(a, b):
              assert len(a) == len(b)
```

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n = len(a)
if len(a) <= 3:
    # TODO: do stuff
    pass
A2 = a[:n/2], A1 = a[n/2:]
A2 = a[:n/2], A1 = a[n/2:]
C1 = mult(A1, B1)
C2 = mult(A2, B2)
C3 = mult(add(A1, A2), add(B1, B2))
return add(add(shift(C1, n), shift(sub(sub(C3, C1), C2), n/2)), C2)

In [135]: assert multiply_1([1, 1, 0], [1, 1, 1]) == [1, 0, 1, 0, 1, 0]
          assert multiply_1([1, 0], [0, 1]) == [1, 0]

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Refinement (3-way divide):  $T(n) = 5T(n/3) + \Theta(n)$

Schonhage-Strassen '71:  $O(n \log n \log \log n)$

Furer '07:  $O(n \log n \log^* n)$

Open question: can multiplication be done in  $O(n \log n)$ ?

## 2 Matrix Multiplication

Given  $n \times n$  matrices  $A, B \in \mathbb{R}^{n \times n}$ , compute  $n \times n$  matrix  $C = AB$ .

Trivial solution is  $O(n^3)$ .

Strassen's Algorithm ([https://en.wikipedia.org/wiki/Strassen\\_algorithm](https://en.wikipedia.org/wiki/Strassen_algorithm)): We note that we can subdivide each matrix into 4 quadrants, resulting in only needing  $8T(n/2) + \Theta(n^2) = O(n^3)$ .

But we can use matrix substructure to only need 7 multiplications.

$$A = \begin{bmatrix} A_{1,1} & A_{1,2} \\ A_{2,1} & A_{2,2} \end{bmatrix}, B = \begin{bmatrix} B_{1,1} & B_{1,2} \\ B_{2,1} & B_{2,2} \end{bmatrix}, C = \begin{bmatrix} C_{1,1} & C_{1,2} \\ C_{2,1} & C_{2,2} \end{bmatrix}$$

$$M_1 := (A_{1,1} + A_{2,2})(B_{1,1} + B_{2,2})$$

$$M_2 := (A_{2,1} + A_{2,2})B_{1,1}$$

$$M_3 := A_{1,1}(B_{1,2} - B_{2,2})$$

$$M_4 := A_{2,2}(B_{2,1} - B_{1,1})$$

$$M_5 := (A_{1,1} + A_{1,2})B_{2,2}$$

$$M_6 := (A_{2,1} - A_{1,1})(B_{1,1} + B_{1,2})$$

$$M_7 := (A_{1,2} - A_{2,2})(B_{2,1} + B_{2,2})$$

$$C_{1,1} = M_1 + M_4 - M_5 + M_7$$

$$C_{1,2} = M_3 + M_5$$

$$C_{2,1} = M_2 + M_4$$

$$C_{2,2} = M_1 - M_2 + M_3 + M_6$$

So overall is  $T(n) = 7T(n/2) + \Theta(n^2) = O(n^{\log_2 7}) = O(n^{2.8})$

Current state-of-the-art: [https://en.wikipedia.org/wiki/Coppersmith%E2%80%93Winograd\\_algorithm](https://en.wikipedia.org/wiki/Coppersmith%E2%80%93Winograd_algorithm)