Chapter 8

Fast Fourier Transform

By Sariel Har-Peled, September 23, 2021

"But now, reflecting further, there begins to creep into his breast a touch of fellow-feeling for his imitators. For it seems to him now that there are but a handful of stories in the world; and if the young are to be forbidden to prey upon the old then they must sit for ever in silence.”

– J.M. Coetzee,

8.1. Introduction

In this chapter, we will address the problem of multiplying two polynomials quickly.

Definition 8.1.1. A polynomial \( p(x) \) of degree \( n \) is a function of the form \( p(x) = \sum_{j=0}^{n} a_j x^j = a_0 + x(a_1 + x(a_2 + \ldots + xa_n)) \).

Note, that given \( x_0 \), the polynomial can be evaluated at \( x_0 \) in \( O(n) \) time.

There is a “dual” (and equivalent) representation of a polynomial. We sample its value in enough points, and store the values of the polynomial at those points. The following theorem states this formally. We omit the proof as you should have seen it already at some earlier math class.

Theorem 8.1.2. For any set \( \{(x_0, y_0), (x_1, y_1), \ldots, (x_{n-1}, y_{n-1})\} \) of \( n \) point-value pairs such that all the \( x_k \) values are distinct, there is a unique polynomial \( p(x) \) of degree \( n - 1 \), such that \( y_k = p(x_k) \), for \( k = 0, \ldots, n - 1 \).

An explicit formula for \( p(x) \) as a function of those point-value pairs is

\[
p(x) = \sum_{i=0}^{n-1} y_i \frac{\prod_{j \neq i} (x-x_j)}{\prod_{j \neq i} (x_i-x_j)}.
\]

Note, that the \( i \)th term in this summation is zero for \( X = x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_{n-1} \), and is equal to \( y_i \) for \( x = x_i \).

It is easy to verify that given \( n \) point-value pairs, we can compute \( p(x) \) in \( O(n^2) \) time (using the above formula).

The point-value pairs representation has the advantage that we can multiply two polynomials quickly. Indeed, if we have two polynomials \( p \) and \( q \) of degree \( n - 1 \), both represented by \( 2n \) (we are using more points than we need) point-value pairs

\[
\{(x_0, y_0), (x_1, y_1), \ldots, (x_{2n-1}, y_{2n-1})\} \quad \text{for} \quad p(x),
\]

and \( \{(x_0, y_0'), (x_1, y_1'), \ldots, (x_{2n-1}, y_{2n-1}')\} \quad \text{for} \quad q(x) \).

This work is licensed under the Creative Commons Attribution-Noncommercial 3.0 License. To view a copy of this license, visit http://creativecommons.org/licenses/by-nc/3.0/ or send a letter to Creative Commons, 171 Second Street, Suite 300, San Francisco, California, 94105, USA.
Let \( r(x) = p(x)q(x) \) be the product of these two polynomials. Computing \( r(x) \) directly requires \( O(n^2) \) using the naive algorithm. However, in the point-value representation we have, that the representation of \( r(x) \) is
\[
\{(x_0, r(x_0)), \ldots, (x_{2n-1}, r(x_{2n-1}))\} = \{(x_0, p(x_0)q(x_0)), \ldots, (x_{2n-1}, p(x_{2n-1})q(x_{2n-1}))\}
\]
Namely, once we computed the representation of \( p(x) \) and \( q(x) \) using point-value pairs, we can multiply the two polynomials in linear time. Furthermore, we can compute the standard representation of \( r(x) \) from this representation.

Thus, if could translate quickly (i.e., \( O(n \log n) \) time) from the standard representation of a polynomial to point-value pairs representation, and back (to the regular representation) then we could compute the product of two polynomials in \( O(n \log n) \) time. The Fast Fourier Transform is a method for doing exactly this. It is based on the idea of choosing the \( x_i \) values carefully and using divide and conquer.

### 8.2. Computing a polynomial quickly on \( n \) values

In the following, we are going to assume that the polynomial we work on has degree \( n - 1 \), where \( n = 2^k \).

If this is not true, we can pad the polynomial with terms having zero coefficients.

Assume that we magically were able to find a set of numbers \( \Psi = \{x_1, \ldots, x_n\} \), so that it has the following property: \( |\text{SQ}(\Psi)| = n/2 \), where \( \text{SQ}(\Psi) = \{x^2 \mid x \in \Psi\} \). Namely, when we square the numbers of \( \Psi \), we remain with only \( n/2 \) distinct values, although we started with \( n \) values. It is quite easy to find such a set.

What is much harder is to find a set that have this property repeatedly. Namely, \( \text{SQ}(|\text{SQ}(\Psi)|) \) would have \( n/4 \) distinct values, \( \text{SQ}(\text{SQ}(\text{SQ}(\Psi))) \) would have \( n/8 \) values, and \( \text{SQ}'(\Psi) \) would have \( n/2^i \) distinct values.

Predictably, maybe, it is easy to show that there is no such set of real numbers (verify...). But let us for the time being ignore this technicality, and fly, for a moment, into the land of fantasy, and assume that we do have such a set of numbers, so that \( |\text{SQ}'(\Psi)| = n/2^i \) numbers, for \( i = 0, \ldots, k \). Let us call such a set of numbers **collapsible**.

Given a set of numbers \( \mathcal{X} = \{x_0, \ldots, x_n\} \) and a polynomial \( p(x) \), let
\[
p(\mathcal{X}) = \{(x_0, p(x_0)), \ldots, (x_n, p(x_n))\}.
\]

Furthermore, let us rewrite \( p(x) = \sum_{i=0}^{n-1} a_i x^i \) as \( p(x) = u(x^2) + x \cdot v(x^2) \), where
\[
u(y) = \sum_{i=0}^{n/2-1} a_{2i+1} y^i \quad \text{and} \quad v(y) = \sum_{i=0}^{n/2-1} a_{2i+2} y^i.
\]

Namely, we put all the even degree terms of \( p(x) \) into \( u(\cdot) \), and all the odd degree terms into \( v(\cdot) \). The maximum degree of the two polynomials \( u(y) \) and \( v(y) \) is \( n/2 \).

We are now ready for the kill: To compute \( p(\Psi) \) for \( \Psi \), which is a collapsible set, we have to compute \( u(\text{SQ}(\Psi)), v(\text{SQ}(\Psi)) \). Namely, once we have the value-point pairs of \( u(\text{SQ}(A)), v(\text{SQ}(A)) \) we can, in linear time, compute \( p(\Psi) \). But, \( \text{SQ}(\Psi) \) have \( n/2 \) values because we assumed that \( \Psi \) is collapsible. Namely, to compute \( n \) point-value pairs of \( p(\cdot) \), we have to compute \( n/2 \) point-value pairs of two polynomials of degree \( n/2 \) over a set of \( n/2 \) numbers.
FFTAlg \( p, X \)

**input:** \( p(x) \): A polynomial of degree \( n \): \( p(x) = \sum_{i=0}^{n-1} a_i x^i \)

**X:** A collapsible set of \( n \) elements.

**output:** \( p(X) \)

begin

\( u(y) = \sum_{i=0}^{n/2-1} a_{2i} y^i \)

\( v(y) = \sum_{i=0}^{n/2-1} a_{1+2i} y^i \).

\( Y = SQ(X) = \{ x^2 \mid x \in X \} \).

\( U = FFTAlg(u, Y) \quad \text{/*/ } U = u(Y) */\)

\( V = FFTAlg(v, Y) \quad \text{/*/ } V = v(Y) */\)

\( Out \leftarrow \emptyset \)

for \( x \in A \) do

\( p(x) = u(x^2) + x \cdot v(x^2) */\)

\( U[x^2] \) is the value \( u(x^2) */\)

\( (x, p(x)) \leftarrow (x, U[x^2] + x \cdot V[x^2]) \)

\( Out \leftarrow Out \cup \{(x, p(x))\} \)

end

return \( Out \)

end

Figure 8.1: The FFT algorithm.

Namely, we reduce a problem of size \( n \) into two problems of size \( n/2 \). The resulting algorithm is depicted in Figure 8.1.

What is the running time of FFTAlg? Well, clearly, all the operations except the recursive calls takes \( O(n) \) time (assume, for the time being, that we can fetch \( U[x^2] \) in \( O(1) \) time). As for the recursion, we call recursively on a polynomial of degree \( n/2 \) with \( n/2 \) values (\( \Psi \) is collapsible!). Thus, the running time is \( T(n) = 2T(n/2) + O(n) \), which is \( O(n \log n) \) – exactly what we wanted.

### 8.2.1. Generating Collapsible Sets

Nice! But how do we resolve this “technicality” of not having collapsible set? It turns out that if we work over the complex numbers (instead of over the real numbers), then generating collapsible sets is quite easy. Describing complex numbers is outside the scope of this writeup, and we assume that you already have encountered them before. Nevertheless a quick reminder is provided in Section 8.4.1. Everything you can do over the real numbers you can do over the complex numbers, and much more (complex numbers are your friend).

In particular, the polynomial \( x^n = 1 \) has \( n \) distinct solutions over the complex numbers. Let \( \gamma_j(n) \) denote the \( j \)th such solution, depicted in Figure 8.2. In particular, the \( n \) roots of unity are

\[
\gamma_j(n) = \cos \left( \frac{2\pi j}{n} \right) + i \sin \left( \frac{2\pi j}{n} \right) \quad \text{for} \quad j = 0, \ldots, n - 1.
\]

Note that \( \gamma_j(n) = (\gamma_1(n))^j \), and \( \gamma_{j+n}(n) = \gamma_j(n) \), for all \( j \). As such, the \( n \) roots of unity form a cyclic group under multiplication, with \( \gamma_1(n) \) being a generator.
Let $\mathcal{A}(n) = \{\gamma_0(n), \ldots, \gamma_{n-1}(n)\}$. It is easy to verify that $|\text{SQ}(\mathcal{A}(n))|$ has exactly $n/2$ elements. Specifically, we have that $\text{SQ}(\mathcal{A}(n)) = \mathcal{A}(n/2)$, as can be easily verified. Namely, if we pick $n$ to be a power of 2, then $\mathcal{A}(n)$ is the required collapsible set.

**Theorem 8.2.1.** Given polynomial $p(x)$ of degree $n$, where $n$ is a power of two, then we can compute $p(X)$ in $O(n \log n)$ time, where $X = \mathcal{A}(n)$ is the set of $n$ roots of unity over the complex numbers.

We can now multiply two polynomials quickly by transforming them to the point-value pairs representation over the $\mathcal{A}(n)$ roots of unity, but we still have to transform this representation back to the regular representation.

### 8.3. Recovering the polynomial

This part of the writeup is somewhat more technical. Putting it shortly, we are going to apply the FFTAlg algorithm once again to recover the original polynomial. The details follow.

It turns out that we can interpret the FFT as a matrix multiplication operator. Indeed, if we have $p(x) = \sum_{i=0}^{n-1} a_i x^i$ then evaluating $p(\cdot)$ on $\mathcal{A}(n)$ is equivalent to:

$$
\begin{pmatrix}
  y_0 \\
  y_1 \\
  y_2 \\
  \vdots \\
  y_{n-1}
\end{pmatrix}
= 
\begin{pmatrix}
  1 & \gamma_0 & \gamma_0^2 & \gamma_0^3 & \cdots & \gamma_0^{n-1} \\
  1 & \gamma_1 & \gamma_1^2 & \gamma_1^3 & \cdots & \gamma_1^{n-1} \\
  1 & \gamma_2 & \gamma_2^2 & \gamma_2^3 & \cdots & \gamma_2^{n-1} \\
  \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\
  1 & \gamma_{n-1} & \gamma_{n-1}^2 & \gamma_{n-1}^3 & \cdots & \gamma_{n-1}^{n-1}
\end{pmatrix}
\begin{pmatrix}
  a_0 \\
  a_1 \\
  a_2 \\
  a_3 \\
  \vdots \\
  a_{n-1}
\end{pmatrix},
$$

where $y_j = \gamma_j(n) = (\gamma_1(n))^j$, and $y_j = p(\gamma_j)$.

This matrix $V$ is quite interesting, and is the **Vandermonde** matrix. Let $V^{-1}$ be the inverse matrix of this Vandermonde matrix. And let multiply the above formula from the left. We get:

$$
\begin{pmatrix}
  a_0 \\
  a_1 \\
  a_2 \\
  a_3 \\
  \vdots \\
  a_{n-1}
\end{pmatrix} = V^{-1}
\begin{pmatrix}
  y_0 \\
  y_1 \\
  y_2 \\
  \vdots \\
  y_{n-1}
\end{pmatrix}.
$$

Namely, we can recover the polynomial $p(x)$ from the point-value pairs

$$
\{(y_0, p(\gamma_0)), (y_1, p(\gamma_1)), \ldots, (y_{n-1}, p(\gamma_{n-1}))\}
$$

by doing a single matrix multiplication of $V^{-1}$ by the vector $[y_0, y_1, \ldots, y_{n-1}]$. However, multiplying a vector with $n$ entries with a matrix of size $n \times n$ takes $O(n^2)$ time. Thus, so far there is no benefit.

However, since the Vandermonde matrix is so well behaved\(^2\), it is not too hard to figure out the inverse matrix.

\(^2\)Not to mention famous, beautiful and well known – in short a celebrity matrix.
Claim 8.3.1. Let $V$ be the $n \times n$ Vandermonde matrix. We have that

$$V^{-1} = \frac{1}{n} \begin{pmatrix}
1 & \beta_0 & \beta_0^2 & \beta_0^3 & \cdots & \beta_0^{n-1} \\
1 & \beta_1 & \beta_1^2 & \beta_1^3 & \cdots & \beta_1^{n-1} \\
1 & \beta_2 & \beta_2^2 & \beta_2^3 & \cdots & \beta_2^{n-1} \\
1 & \beta_3 & \beta_3^2 & \beta_3^3 & \cdots & \beta_3^{n-1} \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
1 & \beta_{n-1} & \beta_{n-1}^2 & \beta_{n-1}^3 & \cdots & \beta_{n-1}^{n-1}
\end{pmatrix},$$

where $\beta_j = 1/\gamma_j(n) = 1/\gamma_{-j}(n)$.

Proof: Consider the $(u, v)$ entry in the matrix $C = V^{-1}V$. We have

$$C_{u,v} = \sum_{j=0}^{n-1} \frac{(\beta_u)^j (\gamma_j)^v}{n}.$$

We use here that $\gamma_j = (\gamma_1)^j$ as can be easily verified. Thus,

$$C_{u,v} = \frac{\sum_{j=0}^{n-1} (\beta_u)^j (\gamma_1)^v}{n} = \frac{\sum_{j=0}^{n-1} (\beta_u)^j ((\gamma_1)^{v-j})}{n} = \sum_{j=0}^{n-1} \frac{(\beta_u \gamma_v)^j}{n}.$$

Clearly, if $u = v$ then

$$C_{u,u} = \frac{1}{n} \sum_{j=0}^{n-1} (\beta_u \gamma_u)^j = \frac{1}{n} \sum_{j=0}^{n-1} (1)^j = \frac{n}{n} = 1.$$

If $u \neq v$ then,

$$\beta_u \gamma_v = (\gamma_u)^{-1} \gamma_v = (\gamma_1)^{-u} \gamma_v = (\gamma_1)^{v-u} = \gamma_{v-u}.$$

And

$$C_{u,v} = \frac{1}{n} \sum_{j=0}^{n-1} (\gamma_{v-u})^j = \frac{1}{n} \cdot \frac{\gamma_{v-u}^n - 1}{\gamma_{v-u} - 1} = \frac{1}{n} \cdot \frac{1 - 1}{\gamma_{v-u} - 1} = 0,$$

this follows by the formula for the sum of a geometric series, and as $\gamma_{v-u}$ is an $n$th root of unity, and as such if we raise it to power $n$ we get 1.

We just proved that the matrix $C$ have ones on the diagonal and zero everywhere else. Namely, it is the identity matrix, establishing our claim that the given matrix is indeed the inverse matrix to the Vandermonde matrix.

Let us recap, given $n$ point-value pairs $\{(y_0, y_0), \ldots, (y_{n-1}, y_{n-1})\}$ of a polynomial $p(x) = \sum_{i=0}^{n-1} a_i x^i$ over the set of $n$th roots of unity, then we can recover the coefficients of the polynomial by multiplying the vector $[y_0, y_1, \ldots, y_n]$ by the matrix $V^{-1}$. Namely,

$$\begin{pmatrix}
a_0 \\
a_1 \\
a_2 \\
\vdots \\
a_{n-1}
\end{pmatrix} = \frac{1}{n} V^{-1} \begin{pmatrix}
y_0 \\
y_1 \\
y_2 \\
\vdots \\
y_{n-1}
\end{pmatrix}.$$
Let us write a polynomial $W(x) = \sum_{i=0}^{n-1} (\gamma_i/n)x^i$. It is clear that $a_i = W(\beta_i)$. That is to recover the coefficients of $p(\cdot)$, we have to compute a polynomial $W(\cdot)$ on $n$ values: $\beta_0, \ldots, \beta_{n-1}$.

The final stroke, is to observe that \{$\beta_0, \ldots, \beta_{n-1}$\} = \{$\gamma_0, \ldots, \gamma_{n-1}$\}; indeed $\beta_i^n = (\gamma^{-1}_i)^n = (\gamma^n_i)^{-1} = 1^{-1} = 1$. Namely, we can apply the FFTAlg algorithm on $W(x)$ to compute $a_0, \ldots, a_{n-1}$.

We conclude:

**Theorem 8.3.2.** *Given $n$ point-value pairs of a polynomial $p(x)$ of degree $n-1$ over the set of $n$ powers of the $n$th roots of unity, we can recover the polynomial $p(x)$ in $O(n \log n)$ time.*

**Theorem 8.3.3.** *Given two polynomials of degree $n$, they can be multiplied in $O(n \log n)$ time.*

### 8.4. The Convolution Theorem

Given two vectors: $A = [a_0, a_1, \ldots, a_n]$ and $B = [b_0, \ldots, b_n]$, their dot product is the quantity

$$A \cdot B = \langle A, B \rangle = \sum_{i=0}^{n} a_i b_i.$$ 

Let $A_r$ denote the shifting of $A$ by $n - r$ locations to the left (we pad it with zeros; namely, $a_j = 0$ for $j \not\in \{0, \ldots, n\}$).

$$A_r = [a_{n-r}, a_{n+1-r}, a_{n+2-r}, \ldots, a_{2n-r}]$$

where $a_j = 0$ if $j \not\in \{0, \ldots, n\}$.

**Observation 8.4.1.** $A_n = A$.

**Example 8.4.2.** For $A = [3, 7, 9, 15]$, $n = 3$

- $A_2 = [7, 9, 15, 0]$,
- $A_5 = [0, 0, 3, 7]$.
Since part, define the following functions by their Taylor expansion $H$ and $A$.

**8.4.1. Complex numbers – a quick reminder**

A complex number is a pair of real numbers $x$ and $y$, written as $\tau = x + iy$, where $x$ is the **real** part and $y$ is the **imaginary** part. Here $i$ is of course the root of $-1$. In **polar form**, we can write $\tau = r \cos \phi + ir \sin \phi = r (\cos \phi + i \sin \phi) = re^{i\phi}$, where $r = \sqrt{x^2 + y^2}$ and $\phi = \arcsin(y/x)$. To see the last part, define the following functions by their Taylor expansion

\[
\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \cdots,
\]

\[
\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \cdots,
\]

and \[e^x = 1 + \frac{x}{1!} + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots.\]

Since $i^2 = -1$, we have that

\[e^{ix} = 1 + i \frac{x}{1!} - \frac{x^2}{2!} - i \frac{x^3}{3!} + \frac{x^4}{4!} + i \frac{x^5}{5!} - \frac{x^6}{6!} + \cdots = \cos x + i \sin x.\]
The nice thing about polar form, is that given two complex numbers \( \tau = r e^{i\phi} \) and \( \tau' = r' e^{i\phi'} \), multiplying them is now straightforward. Indeed, \( \tau \cdot \tau' = r e^{i\phi} \cdot r' e^{i\phi'} = rr' e^{i(\phi+\phi')} \). Observe that the function \( e^{i\phi} \) is \( 2\pi \) periodic (i.e., \( e^{i\phi} = e^{i(\phi+2\pi)} \)), and \( 1 = e^{i0} \). As such, an \( n \)th root of \( 1 \), is a complex number \( \tau = r e^{i\phi} \) such that \( \tau^n = r^n e^{i0} = e^{i0} \). Clearly, this implies that \( r = 1 \), and there must be an integer \( j \), such that

\[
n\phi = 0 + 2\pi j \implies \phi = j(2\pi/n).
\]

These are all distinct values for \( j = 0, \ldots, n - 1 \), which are the \( n \) distinct roots of unity.

Bibliography