01204211 Discrete Mathematics
Lecture 10b: Polynomials (2)[1]

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[1] This section is from Berkeley CS70 lecture notes.

Fun fact: Check digit for Thai National ID

Review: Polynomials

A **single-variable polynomial** is a function $p(x)$ of the form

$$p(x) = a_d x^d + a_{d-1} x^{d-1} + \cdots + a_1 x + a_0.$$

We call a_i's *coefficients*. Usually, variable x and coefficients a_i's are real numbers. The **degree** of a polynomial is the largest exponent of the terms with non-zero coefficients.

Review: Basic facts

Definition

a is a **root** of polynomial $f(x)$ if $f(a) = 0$.

Properties

Property 1: A non-zero polynomial of degree d has at most d roots.
Property 2: Given $d+1$ pairs $(x_1, y_1), \ldots, (x_{d+1}, y_{d+1})$ with distinct x_i's, there is a *unique* polynomial $p(x)$ of degree at most d such that $p(x_i) = y_i$ for $1 \leq i \leq d+1$.

Polynomial division

Polynomial division

If you have a polynomial $p(x)$ of degree d, you can divide it with a polynomial $q(x)$ of degree $\leq d$. You have that there exists a pair of polynomial $q'(x)$ and $r(x)$ such that

$$p(x) = q'(x)q(x) + r(x),$$

and $r(x)$ is of degree **less** than $q(x)$'s degree.

Lemma 1

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Dividing $p(x)$ with $(x-a)$, we get that

$$p(x) = q'(x)(x-a) + r(x),$$

where $r(x)$ is of degree at most $1-1=0$, i.e., $r(x)$ must be a constant; thus, we assume that $r(x) = c$. Let's evaluate $p(a)$; note that $p(a) = c$, since

$$p(a) = q'(a)(a-a) + c = 0 + c = c.$$

However we know that a is a root of $p(x)$, i.e., $p(a) = 0$. Therefore $c = 0$, or $r(x) = 0$. Thus, the lemma follows. $\square$

Lemma 2

If $p(x)$ *is a polynomial of degree* d *with* d *distinct roots* $a_1, a_2, \ldots, a_d$, $p(x)$ *can be written as* $c(x-a_1)(x-a_2)\cdots(x-a_d)$.

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where $q(x)$ is a polynomial of degree d with d distinct roots $a_1, \ldots, a_d$. $\square$

Property 1

Polynomials over a finite field $GF(p)$

Examples - evaluation

Suppose that we work over $GF(m)$ where $m = 11$. Let $p(x) = 4 \cdot x^2 + 5 \cdot x + 3$. We have

x	$p(x)$	$p(x) \bmod m$
0	3	3
1	12	1
2	29	7
3	54	10
4	87	10
5	128	7
6	177	1
7	234	3
8	299	2
9	372	9
10	453	2
11	542	3

Examples - interpolation

Let $m = 11$. Suppose that $p(x)$ is a polynomial over $GF(m)$ of degree 2 passing through $(2,7),(4,10)$, and $(7,3)$. Find $p(x)$.
Let

- $\Delta_1(x) = \frac{(x-4)(x-7)}{(2-4)(2-7)} = \frac{x^2-11x+28}{(-2)\cdot(-5)} = \frac{x^2+6}{10} = 10x^2 + 5$
- $\Delta_2(x) = \frac{(x-2)(x-7)}{(4-2)(4-7)} = \frac{x^2-9x+14}{2\cdot(-3)} = \frac{x^2+2x+3}{5} = 9x^2 + 7x + 5$
- $\Delta_2(x) = \frac{(x-2)(x-4)}{(7-2)(7-4)} = \frac{x^2-6x+8}{5\cdot 3} = \frac{x^2+5x+8}{4} = 3x^2 + 4x + 2$

Thus,

$$\begin{aligned} p(x) &= 7\Delta_1(x) + 10\Delta_2(x) + 3\Delta_3(x) \\ &= (70x^2 + 35) + (90x^2 + 70x + 50) + (9x^2 + 12x + 6) \\ &= 4x^2 + 5x + 3 \end{aligned}$$

How many?

Two ways of specifying a polynomial $p(x)$ of degree d:

- Specify its coefficients $a_0, a_1, \ldots, a_d$, i.e., the polynomial is

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- Specify its coefficients $a_0, a_1, \dots, a_d$, i.e., the polynomial is

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- Specify $d + 1$ points, i.e., $(x_1, y_1), (x_2, y_2), \dots, (x_{d+1}, y_{d+1})$, where all x_i are distinct. There is a *unique* polynomial $p(x)$ of degree at most d that passes through these points (from Property 2).

For polynomials of degree at most d over $GF(m)$, if you specify q points, there are:

q	numbers of polynomials
$d+1$	1
d	m
$d-1$	m^2
$d-2$	m^3
$\vdots$	$\vdots$
1	m^d
0	m^{d+1}

Secret sharing scheme - settings

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- There are n people, a secret s, and an integer k.
- We want to "distribute" the secret in such a way that any set of $k-1$ people cannot know anything about s, but any set of k people can reconstruct s.

Secret sharing scheme

Secret sharing scheme

- Pick m to be larger than n and s. (Much larger than s, i.e., $m >>> s$.)
- Pick a random polynomial of degree $k-1$ such that $P(0) = s$.
- Give $P(i)$ to person i, for $1 \leq i \leq n$.
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- Correctness: for any set of $k-1$ people, how many possible candidate secrets compatible with the information these people have?

A more complex secret sharing scheme

Suppose that a company has 3 VPs and 5 senior members. You want to distribute a secret such that (1) any 2 VPs can obtain the secret or (2) a single VP with 3 senior members can also obtain the secret. How can you do that?

Sending a message

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Lossy internet:

Erasure codes

Suppose that we want to send a message $m_1, m_2, \ldots, m_n$ where $m_i \leq p - 1$ for some prime p.

However, we know that our communication channel is lossy, i.e., some messages can be *dropped*. How can we send this message?

Two ways of encoding

Suppose that we want to send a message $m_1, m_2, \ldots, m_n$ where $m_i \leq p - 1$ for some prime p. We want to tolerate up to k missing messages.
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We use a polynomial of degree $n-1$ and generate $n+k$ points.
How can we obtain the polynomial $P(x)$?

- We can let the message be the coefficients, i.e., let

$$P(x) = m_n \cdot x^{n-1} + m_{n-1} \cdot x^{n-2} + \cdots + m_2 \cdot x + m_1.$$

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$$P(x) = m_n \cdot x^{n-1} + m_{n-1} \cdot x^{n-2} + \cdots + m_2 \cdot x + m_1.$$

- We can try to obtain a degree-$(n-1)$ polynomial $P(x)$ such that

$$P(0) = m_1,\ P(1) = m_2,\ \ldots P(n-2) = m_{n-1},\ P(n-1) = m_n.$$