

ANALOGIES WITH POLYNOMIALS

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1. THE BASIC ANALOGIES

Similarities between \mathbf{Z} and $F[T]$ are an important theme in number theory. The following table collects some analogous concepts in \mathbf{Z} and in $F[T]$.

\mathbf{Z}	$F[T]$	Similarity
± 1	nonzero constants	the units
prime	irreducible	have only trivial factors
$ n $	$\deg f$	role in division theorem
positive	monic (lead. coeff = 1)	standard unit multiple

A polynomial is called *monic* when it has leading coefficient 1, such as $T^2 + 7T + 3$ but not $2T^2 + 5T - 1$. Every nonzero polynomial in $F[T]$ has exactly one monic constant multiple: just multiply through the polynomial by the inverse of the leading coefficient.

Example 1.1. In $\mathbf{Q}[T]$, the monic constant multiple of $2T^2 + 5T - 1$ is $\frac{1}{2}(2T^2 + 5T - 1) = T^2 + \frac{5}{2}T - \frac{1}{2}$. In \mathbf{F}_7 , $2 \cdot 4 = 1$, so the monic constant multiple of $2T^2 + 5T - 1$ in $\mathbf{F}_7[T]$ is $4(2T^2 + 5T - 1) = T^2 + 6T + 3$.

Positive integers are closed under multiplication and monic polynomials are closed under multiplication. Positive integers are also closed under addition but monic polynomials are *not* generally closed under addition. This is an important difference!

By definition, a prime in \mathbf{Z} is a number which is not ± 1 and its only factors are ± 1 and \pm itself. Similarly, a polynomial in $F[T]$ is called irreducible when it is nonconstant (that is, is not a unit) and its only factors are nonzero constants and nonzero constant multiples of itself. Primes are usually written as p and irreducible polynomials are usually written as $p(T)$ or $\pi(T)$. (This use of the letter π has nothing to do with the number 3.1415926...)

Here are some analogous results in \mathbf{Z} and $F[T]$:

- (1) In \mathbf{Z} , $|mn| = |m||n|$. In $F[T]$, $\deg fg = \deg f + \deg g$.
- (2) The units in \mathbf{Z} have absolute value 1 (which is the smallest absolute value possible for nonzero integers) and the units in $F[T]$ have degree 0 (the smallest degree possible for nonzero polynomials).
- (3) In \mathbf{Z} if $a|b$ then $|a| \leq |b|$. In $F[T]$, if $f|g$ then $\deg f \leq \deg g$.
- (4) If $a|b$ and $b|a$ in \mathbf{Z} then $a = \pm b$, while if $f|g$ and $g|f$ in $F[T]$ then $f = cg$ for some nonzero constant c .
- (5) Every integer other than 0 and ± 1 is a product of primes (allowing negative primes!), while every polynomial in $F[T]$ other than a constant is a product of irreducible polynomials.

The most important similarity between \mathbf{Z} and $F[T]$ is the division theorem in both settings. We state them without proof, using similar wording.

Theorem 1.2. For $a, b \in \mathbf{Z}$ with $b \neq 0$, there are unique q and r in \mathbf{Z} such that $a = bq + r$ with $0 \leq r < |b|$.

Theorem 1.3. For $f, g \in F[T]$ with $g \neq 0$, there are unique q and r in $F[T]$ such that $f = gq + r$ with $r = 0$ or $\deg r < \deg g$.

The greatest common divisor of two integers is the common divisor largest in size (so always positive). In $F[T]$, the greatest common divisor of two polynomials is the common monic factor with the largest degree. Examples will be worked out in the next section.

Two integers are called relatively prime when their only common factors are ± 1 . Similarly, two polynomials in $F[T]$ are called relatively prime when their only common factors are nonzero constants. In both \mathbf{Z} and $F[T]$, relative primality means the only common factors are units (± 1 in \mathbf{Z} and nonzero constants in $F[T]$). Euclid's algorithm is the standard method to compute greatest common divisors in \mathbf{Z} (so, in particular, to determine relative primality) while a variant of Euclid's algorithm in $F[T]$ will perform the same role for polynomials.

The standard chain of reasoning

div. thm. \rightsquigarrow Euclid \rightsquigarrow Bezout \rightsquigarrow if $p|ab$ then $p|a$ or $p|b$ \rightsquigarrow unique factorization

in \mathbf{Z} , where p is a prime, carries over to $F[T]$ nearly *verbatim*, with only minor changes needed in most proofs:

div. thm. \rightsquigarrow Euclid \rightsquigarrow Bezout \rightsquigarrow if $\pi|fg$ then $\pi|f$ or $\pi|g$ \rightsquigarrow unique factorization,

where π is an irreducible.

There is one important *difference* between \mathbf{Z} and $F[T]$. Division in \mathbf{Z} involves remainders ≥ 0 , so if two integers are relatively prime Euclid's algorithm will *always* have last nonzero remainder 1. But this is false with polynomials: the last nonzero remainder in Euclid's algorithm for polynomials might be a nonzero constant other than 1, so writing an $F[T]$ -linear combination of relatively prime polynomials as 1 can involve some additional scaling which we don't have to do in \mathbf{Z} .

Example 1.4. In $\mathbf{R}[T]$, let $f(T) = T^2 + 1$ and $g(T) = T - 1$. Certainly $f(T)$ and $g(T)$ are relatively prime: they have no common factor in $\mathbf{R}[T]$ other than nonzero constants. When we carry out Euclid's algorithm on these two polynomials we find

$$\begin{aligned} T^2 + 1 &= (T - 1)(T + 1) + 2 \\ T - 1 &= 2 \left(\frac{1}{2}T - \frac{1}{2} \right) + 0, \end{aligned}$$

so the last nonzero remainder is 2. This is a nonzero constant in $\mathbf{R}[T]$ but it is not 1. By *convention* we normalize the gcd of two polynomials to be monic, so the gcd of $T^2 + 1$ and $T - 1$ is called 1, not 2.

2. EUCLID AND BEZOUT: EXAMPLES

Bezout's identity in \mathbf{Z} says for a and b in \mathbf{Z} that we can write

$$ax + by = (a, b)$$

for some integers x and y . Values for x and y can be found by using back-substitution into Euclid's algorithm for a and b . Similarly, Bezout's identity for $F[T]$ says for $f(T)$ and $g(T)$ in $F[T]$ that

$$f(T)u(T) + g(T)v(T) = (f, g),$$

for some $u(T)$ and $v(T)$ in $F[T]$. Here too the polynomials $u(T)$ and $v(T)$ can be found using back-substitution into Euclid's algorithm for $f(T)$ and $g(T)$.

Example 2.1. Let $f(T) = T^4 + T^3 + T^2 + T + 1$ and $g(T) = T^3 - 2T - 4$. We will perform Euclid's algorithm to compute a greatest common divisor of $f(T)$ and $g(T)$ in $F[T]$ for various fields F .

In $\mathbf{Q}[T]$, the gcd of $f(T)$ and $g(T)$ is found as follows:

$$\begin{aligned} T^4 + T^3 + T^2 + T + 1 &= (T^3 - 2T - 4)(T + 1) + (3T^2 + 7T + 5) \\ T^3 - 2T - 4 &= (3T^2 + 7T + 5) \left(\frac{1}{3}T - \frac{7}{9} \right) + \left(\frac{16}{9}T - \frac{1}{9} \right) \\ 3T^2 + 7T + 5 &= \left(\frac{16}{9}T - \frac{1}{9} \right) \left(\frac{27}{16}T + \frac{1035}{256} \right) + \frac{1395}{256} \\ \frac{16}{9}T - \frac{1}{9} &= \frac{1395}{256} \left(\frac{4096}{12555}T - \frac{256}{12555} \right) + 0. \end{aligned}$$

In practice, once we reach a nonzero constant as a remainder we can stop, just as we do when we get a remainder of 1 in Euclid's algorithm for \mathbf{Z} : the next step will definitely have a remainder of 0, so the nonzero constant remainder $\frac{1395}{256}$ will be the last nonzero remainder and there is no point in performing the next step. Since the last nonzero remainder is a nonzero constant, f and g are relatively prime in $\mathbf{Q}[T]$. Even though the last nonzero remainder is not 1, but some other nonzero constant, we still write “ $(f, g) = 1$ ” because (f, g) denotes the *monic* greatest common divisor.

Now we will compute (f, g) in $\mathbf{F}_p[T]$ for small p , with the same $f(T)$ and $g(T)$ as above.

In $\mathbf{F}_2[T]$, $g(T) = T^3$ (the linear and constant terms in $g(T)$ are 0 in \mathbf{F}_2). Then Euclid's algorithm on $f(T)$ and $g(T)$ in $\mathbf{F}_2[T]$ is

$$\begin{aligned} T^4 + T^3 + T^2 + T + 1 &= (T^3)(T + 1) + (T^2 + T + 1) \\ T^3 &= (T^2 + T + 1)(T + 1) + 1, \end{aligned}$$

and we stop at the nonzero constant remainder: $(f, g) = 1$ in $\mathbf{F}_2[T]$.

In $\mathbf{F}_3[T]$, $g(T) = T^3 + T + 2$ and Euclid's algorithm on $f(T)$ and $g(T)$ is

$$\begin{aligned} T^4 + T^3 + T^2 + T + 1 &= (T^3 + T + 2)(T + 1) + (T + 2) \\ T^3 + T + 2 &= (T + 2)(T^2 + T + 2) + 1, \end{aligned}$$

so $(f, g) = 1$ in $\mathbf{F}_3[T]$.

In $\mathbf{F}_5[T]$, $g(T) = T^3 + 3T + 1$ and Euclid's algorithm on $f(T)$ and $g(T)$ is

$$\begin{aligned} T^4 + T^3 + T^2 + T + 1 &= (T^3 + 3T + 1)(T + 1) + (3T^2 + 2T) \\ T^3 + 3T + 1 &= (3T^2 + 2T)(2T + 2) + (4T + 1) \\ 3T^2 + 2T &= (4T + 1)(2T) + 0, \end{aligned}$$

so the last nonzero remainder is *not* constant: $f(T)$ and $g(T)$ have greatest common divisor $4T + 1$ in $\mathbf{F}_5[T]$, so their monic gcd is its monic scalar multiple $(f, g) = -(4T + 1) = T + 4$. We can explicitly factor out $T + 4$ from both f and g in $\mathbf{F}_5[T]$:

$$f(T) = (T + 4)(T^3 + 2T^2 + 3T + 4), \quad g(T) = (T + 4)(T^2 + T + 4).$$

In $\mathbf{F}_7[T]$, $g(T) = T^3 + 5T + 3$ and Euclid's algorithm on $f(T)$ and $g(T)$ is

$$\begin{aligned} T^4 + T^3 + T^2 + T + 1 &= (T^3 + 5T + 3)(T + 1) + (3T^2 + 5) \\ T^3 + 5T + 3 &= (3T^2 + 5)(5T) + (T + 3) \\ 3T^2 + 5 &= (T + 3)(3T + 5) + 4, \end{aligned}$$

and we stop since we have reached a nonzero constant, 4. The gcd of f and g in $\mathbf{F}_7[T]$ is 1.

The following table summarizes our computations. We list both the last nonzero remainder in Euclid's algorithm and the (monic) gcd.

$F[T]$	Last Remainder	(f, g)
$\mathbf{Q}[T]$	1395/256	1
$\mathbf{F}_2[T]$	1	1
$\mathbf{F}_3[T]$	1	1
$\mathbf{F}_5[T]$	$4T + 1$	$T + 4$
$\mathbf{F}_7[T]$	4	1

TABLE 1. $f(T) = T^4 + T^3 + T^2 + T + 1, g(T) = T^3 - 2T - 4$

Remark 2.2. In $\mathbf{F}_5[T]$ there is a nonconstant gcd. There is one other p for which $f(T)$ and $g(T)$ are not relatively prime in $\mathbf{F}_p[T]$: in $\mathbf{F}_{31}[T]$, $(f(T), g(T)) = T - 2$.

Now let's obtain Bezout's identity from the gcd calculations in Example 2.1 by back substitution.

In $\mathbf{Q}[T]$, running Euclid's algorithm on $f(T)$ and $g(T)$ in reverse tells us

$$\begin{aligned} \frac{1395}{256} &= (3T^2 + 7T + 5) - \left(\frac{16}{9}T - \frac{1}{9}\right) \left(\frac{27}{16}T + \frac{1035}{256}\right) \\ &= (3T^2 + 7T + 5) - \left((T^3 - 2T - 4) - (3T^2 + 7T + 5) \left(\frac{1}{3}T - \frac{7}{9}\right)\right) \left(\frac{27}{16}T + \frac{1035}{256}\right) \\ &= (3T^2 + 7T + 5) \left(\frac{9}{16}T^2 + \frac{9}{256}T - \frac{549}{256}\right) - (T^3 - 2T - 4) \left(\frac{27}{16}T + \frac{1035}{256}\right) \\ &\vdots \\ &= f \cdot \left(\frac{9}{16}T^2 + \frac{9}{256}T - \frac{549}{256}\right) + g \cdot \left(-\frac{9}{16}T^3 - \frac{153}{256}T^2 + \frac{27}{64}T - \frac{243}{128}\right). \end{aligned}$$

Multiplying through by the constant 256/1395 makes the left side 1:

$$1 = f \cdot \left(\frac{16}{155}T^2 + \frac{1}{155}T - \frac{61}{155}\right) + g \cdot \left(-\frac{16}{155}T^3 - \frac{17}{155}T^2 + \frac{12}{155}T - \frac{54}{155}\right).$$

Remark 2.3. The common denominator 155 in the last equation factors as $5 \cdot 31$. This is related to the special roles of 5 and 31 in Remark 2.2!

In $\mathbf{F}_2[T]$ we get by back-substitution from Euclid's algorithm

$$\begin{aligned} 1 &= g - (T^2 + T + 1)(T + 1) \\ &= g - (f - g(T + 1))(T + 1) \\ &= f \cdot (T + 1) + g \cdot (1 + (T + 1)(T + 1)) \\ &= f \cdot (T + 1) + g \cdot T^2. \end{aligned}$$

Using back-substitution in $\mathbf{F}_3[T]$,

$$\begin{aligned} 1 &= g - (T + 2)(T^2 + x + 2) \\ &= g - (f - g(T + 1))(T^2 + T + 2) \\ &= f \cdot (2T^2 + 2T + 1) + g \cdot (1 + (T + 1)(T^2 + T + 2)) \\ &= f \cdot (2T^2 + 2T + 1) + g \cdot (T^3 + 2T^2). \end{aligned}$$

In $\mathbf{F}_5[T]$,

$$\begin{aligned} 4T + 1 &= g - (3T^2 + 2T)(2T + 2) \\ &= g - (f - g(T + 1)(2T + 2)) \\ &= f \cdot (3T + 3) + g \cdot (1 + (T + 1)(2T + 2)) \\ &= f \cdot (3T + 3) + g \cdot (2T^2 + 4T + 3). \end{aligned}$$

The gcd we found in Euclid's algorithm, $4T + 1$, is not monic. To write the monic gcd of f and g as an $\mathbf{F}_5[T]$ -linear combination of f and g we simply multiply through the equations by $-1 = 4$:

$$T + 4 = f \cdot (2T + 2) + g \cdot (3T^2 + T + 2).$$

In $\mathbf{F}_7[T]$,

$$\begin{aligned} 4 &= (3T^2 + 5) - (T + 3)(3T + 5) \\ &= (3T^2 + 5) - (g - (3T^2 + 5)(5T))(3T + 5) \\ &= (3T^2 + 5)(1 + 5T(3T + 5)) + g(4T + 2) \\ &= (3T^2 + 5)(T^2 + 4T + 1) + g(4T + 2) \\ &= (f - g(T + 1))(T^2 + 4T + 1) + g(4T + 2) \\ &= f \cdot (T^2 + 4T + 1) + g \cdot (6T^3 + 2T^2 + 6T + 1). \end{aligned}$$

Multiplying through by $4^{-1} = 2$,

$$1 = f \cdot (2T^2 + T + 2) + g \cdot (5T^3 + 4T^2 + 5T + 2).$$

3. SOLVING SIMULTANEOUS CONGRUENCES: AN EXAMPLE

In \mathbf{Z} , if we want to solve the pair of congruence conditions

$$x \equiv 2 \pmod{5}, \quad x \equiv 11 \pmod{19},$$

we lift the first congruence to \mathbf{Z} in the form $x = 2 + 5y$ for some $y \in \mathbf{Z}$ and substitute that into the second congruence and solve for y :

$$2 + 5y \equiv 11 \pmod{19} \Rightarrow 5y \equiv 9 \pmod{19} \Rightarrow y \equiv 17 \pmod{19}.$$

Thus $y = 17 + 19z$ for some integer z , so $x = 2 + 5(17 + 19z) = 87 + 95z$, so $x \equiv 87 \pmod{95}$. Conversely, if $x \equiv 87 \pmod{95}$ then $x \equiv 2 \pmod{5}$ and $x \equiv 11 \pmod{19}$ since 87 fits both conditions and the modulus 95 is divisible by 5 and 19.

We can solve polynomial congruences in the same way. Consider in $\mathbf{F}_5[T]$ the two congruence conditions

$$f(T) \equiv 3T \pmod{T^2 + 1}, \quad f(T) \equiv 2T^2 + 1 \pmod{T^3}.$$

Here the unknown we are looking for is $f(T)$, *not* T : T is just a variable for the polynomials. We want an $f(T)$ in $\mathbf{F}_5[T]$ which fits both congruence conditions.

Lift the first congruence into $\mathbf{F}_5[T]$ by writing it as

$$(3.1) \quad f(T) = 3T + (T^2 + 1)g(T)$$

for some $g(T) \in \mathbf{F}_5[T]$. Substitute this into the second congruence:

$$3T + (T^2 + 1)g(T) \equiv 2T^2 + 1 \pmod{T^3}.$$

Subtracting $3T$ from both sides (note $-3T = 2T$ in $\mathbf{F}_5[T]$),

$$(3.2) \quad (T^2 + 1)g(T) \equiv 2T^2 + 2T + 1 \pmod{T^3}.$$

We now need to invert $T^2 + 1 \pmod{T^3}$. This will be done with Euclid: in $\mathbf{F}_5[T]$,

$$\begin{aligned} T^3 &= (T^2 + 1)T + 4T, \\ T^2 + 1 &= 4T(4T) + 1, \end{aligned}$$

so

$$\begin{aligned} 1 &= T^2 + 1 - 4T(4T) \\ &= T^2 + 1 - 4T(T^3 - (T^2 + 1)T) \\ &= (T^2 + 1)(4T^2 + 1) + T^3(-4T), \end{aligned}$$

so $(T^2 + 1)(4T^2 + 1) \equiv 1 \pmod{T^3}$. Therefore in $\mathbf{F}_5[T]$, the inverse of $T^2 + 1 \pmod{T^3}$ is $4T^2 + 1$, so multiplying both sides of (3.2) by $4T^2 + 1$ gives

$$\begin{aligned} g(T) &\equiv (4T^2 + 1)(2T^2 + 2T + 1) \pmod{T^3} \\ &\equiv 3T^4 + 3T^3 + T^2 + 2T + 1 \pmod{T^3} \\ &\equiv T^2 + 2T + 1 \pmod{T^3}. \end{aligned}$$

Therefore $g(T) = T^2 + 2T + 1 + T^3h(T)$ for some $h(T) \in \mathbf{F}_5[T]$, and substituting this formula for $g(T)$ into (3.1) shows any $f(T)$ fitting the two original congruence conditions has the form

$$\begin{aligned} f(T) &= 3T + (T^2 + 1)(T^2 + 2T + 1 + T^3h(T)) \\ &= T^4 + 2T^3 + 2T^2 + 1 + (T^2 + 1)T^3h(T), \end{aligned}$$

so

$$f(T) \equiv T^4 + 2T^3 + 2T^2 + 1 \pmod{(T^2 + 1)T^3}.$$

As a check that $T^4 + 2T^3 + 2T^2 + 1$ fits the original two congruence conditions, in $\mathbf{F}_5[T]$

$$(T^4 + 2T^3 + 2T^2 + 1) - 3T = (T^2 + 1)(T + 1)$$

and

$$(T^4 + 2T^3 + 2T^2 + 1) - (2T^2 + 1) = T^3(T + 2).$$

Therefore $T^4 + 2T^3 + 2T^2 + 1$ works, and more generally any polynomial congruent to $T^4 + 2T^3 + 2T^2 + 1 \pmod{(T^2 + 1)T^3}$ works. This is the complete set of solutions to both congruences.