

# Basic Number Theory and Finite Fields

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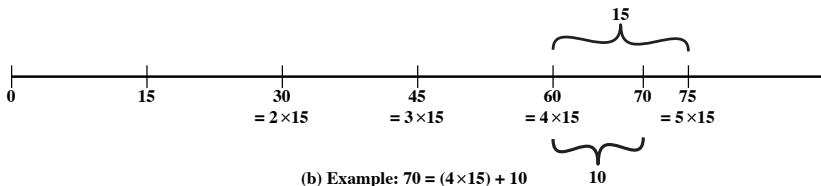
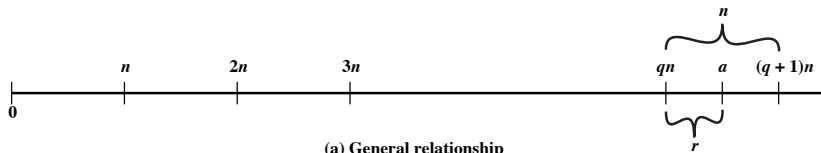
# Divisibility and Division

- 🌐 We say a nonzero integer  $b$  divides another integer  $a$ , denoted as  $b|a$ , if  $a = mb$  for some integer  $m$ .
- 🌐 When an integer  $a$  is divided by a positive integer  $n$ , we get a unique integer **quotient**  $q$  and a unique integer **remainder**  $r$  such that

$$a = qn + r \quad 0 \leq r < n, q = \lfloor a/n \rfloor.$$

- 🌐 The remainder  $r$  is also referred to as a **residue**.

# Quotient and Remainder



Source: Figure 4.1, Stallings 2010

# Essence of the Euclidean Algorithm

- 🌐 Given two integers  $a$  and  $b$  such that  $a \geq b > 0$ .
- 🌐 Let  $a = qb + r$ , where  $0 \leq r < b$ .
- 🌐 There are two cases:
  - ☀ If  $r = 0$ , then we know immediately  $\gcd(a, b) = b$  and stop.
  - ☀ If  $r \neq 0$ , repeat the steps above with  $b$  as  $a$  and  $r$  as  $b$ .
- 🌐 In both cases, the equality  $\gcd(a, b) = \gcd(b, r)$  holds.
  - ☀ Consider  $a = qb + r$ .
  - ☀ Since  $\gcd(b, r) | b$  and  $\gcd(b, r) | r$ , we have  $\gcd(b, r) | a$ .
  - ☀ Both  $\gcd(b, r) | a$  and  $\gcd(b, r) | b$ ; so,  $\gcd(b, r) \leq \gcd(a, b)$ .
  - ☀ Consider  $r = a - qb$ .
  - ☀ Since  $\gcd(a, b) | a$ , and  $\gcd(a, b) | b$ , we have  $\gcd(a, b) | r$ .
  - ☀ Both  $\gcd(a, b) | b$  and  $\gcd(a, b) | r$ ; so,  $\gcd(a, b) \leq \gcd(b, r)$ .

The remainder  $r$  from dividing  $a$  by  $n$  ( $> 0$ ) is usually denoted by “ $a \bmod n$ ”.

$$a = qn + (a \bmod n) \quad q = \lfloor a/n \rfloor.$$

$$11 \bmod 7 = 4 \text{ (because } 11 = 1 \times 7 + 4\text{)}.$$

$$-11 \bmod 7 = 3 \text{ (because } -11 = -2 \times 7 + 3\text{)}.$$

# Congruence Modulo $N$

- Two integers  $a$  and  $b$  are *congruent modulo  $n$*  ( $n > 0$ ), denoted as  $a \equiv b \pmod{n}$ , if  $a \bmod n = b \bmod n$ .
- The positive integer  $n$  is called the *modulus* of the congruence relation.
- If  $a \equiv 0 \pmod{n}$ , then  $n|a$ ; and vice versa.
- If  $a \equiv b \pmod{n}$ , then  $n|(a - b)$ ; and vice versa.

# Modular Arithmetic Operations

Properties:

$$((a \bmod n) + (b \bmod n)) \bmod n = (a + b) \bmod n$$

$$((a \bmod n) - (b \bmod n)) \bmod n = (a - b) \bmod n$$

$$((a \bmod n) \times (b \bmod n)) \bmod n = (a \times b) \bmod n$$

Applications:

$$\begin{aligned} & 11^7 \pmod{13} \\ \equiv & (11 \times 11^2 \times 11^4) \pmod{13} \\ \equiv & (11 \pmod{13}) \times (11^2 \pmod{13}) \times (11^4 \pmod{13}) \\ \equiv & (11 \pmod{13}) \times (4 \pmod{13}) \times (3 \pmod{13}) \\ \equiv & (11 \times 4 \times 3) \pmod{13} \\ \equiv & 2 \pmod{13} \end{aligned}$$

# Arithmetic Modulo 8

+	0	1	2	3	4	5	6	7
0	0	1	2	3	4	5	6	7
1	1	2	3	4	5	6	7	0
2	2	3	4	5	6	7	0	1
3	3	4	5	6	7	0	1	2
4	4	5	6	7	0	1	2	3
5	5	6	7	0	1	2	3	4
6	6	7	0	1	2	3	4	5
7	7	0	1	2	3	4	5	6

(a) Addition modulo 8

×	0	1	2	3	4	5	6	7
0	0	0	0	0	0	0	0	0
1	0	1	2	3	4	5	6	7
2	0	2	4	6	0	2	4	6
3	0	3	6	1	4	7	2	5
4	0	4	0	4	0	4	0	4
5	0	5	2	7	4	1	6	3
6	0	6	4	2	0	6	4	2
7	0	7	6	5	4	3	2	1

(b) Multiplication modulo 8

	$w$	$-w$	$w^{-1}$
0	0	—	—
1	7	1	1
2	6	—	—
3	5	3	3
4	4	—	—
5	3	5	5
6	2	—	—
7	1	7	7

(c) Additive and multiplicative inverses modulo 8



# Residue Classes

Let  $Z_n$  denote the set of nonnegative integers less than  $n$ :

$$Z_n = \{0, 1, 2, \dots, (n-1)\}.$$

This is referred to as the set of residues, or *residue classes*, modulo  $n$ .

Each integer  $r$  in  $Z_n$  represents a residue class  $[r]$ , where

$$[r] = \{a : a \text{ is an integer, } a \equiv r \pmod{n}\}.$$

For example, if the modulus is 4, then

$$[1] = \{\dots, -7, -3, 1, 5, 9, 13, \dots\}.$$

# Principles of Modular Arithmetic

If  $(a + b) \equiv (a + c) \pmod{n}$ , then  $b \equiv c \pmod{n}$ .

If  $(a \times b) \equiv (a \times c) \pmod{n}$ , then  $b \equiv c \pmod{n}$ , only when  $a$  is relatively prime to  $n$ .

$Z_8$		0	1	2	3	4	5	6	7
Multiplied by 6		0	6	12	18	24	30	36	42
Residues		0	6	4	2	0	6	4	2

$(6 \times 3) \equiv (6 \times 7) \pmod{8}$ , but  $3 \not\equiv 7 \pmod{8}$ .

$Z_8$		0	1	2	3	4	5	6	7
Multiplied by 5		0	5	10	15	20	25	30	35
Residues		0	5	2	7	4	1	6	3


Property	Expression
Commutative Laws	$(w + x) \bmod n = (x + w) \bmod n$ $(w \times x) \bmod n = (x \times w) \bmod n$
Associative Laws	$[(w + x) + y] \bmod n = [w + (x + y)] \bmod n$ $[(w \times x) \times y] \bmod n = [w \times (x \times y)] \bmod n$
Distributive Law	$[w \times (x + y)] \bmod n = [(w \times x) + (w \times y)] \bmod n$
Identities	$(0 + w) \bmod n = w \bmod n$ $(1 \times w) \bmod n = w \bmod n$
Additive Inverse ( $-w$ )	For each $w \in Z_n$ , there exists a $z$ such that $w + z \equiv 0 \pmod n$


Source: Table 4.3, Stallings 2010

# Finding the Multiplicative Inverse

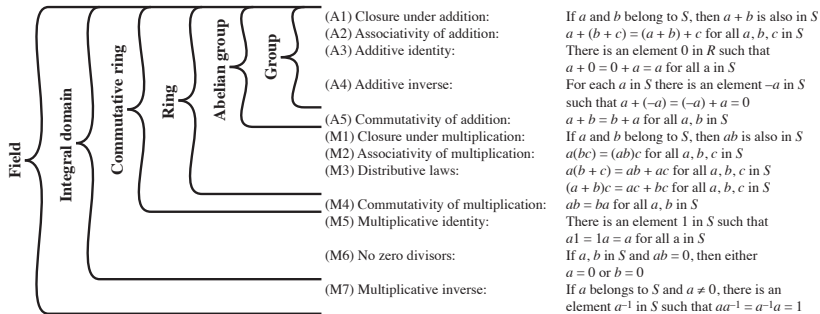
*EXTENDED EUCLID*( $a, b$ ) :

1.  $(X_1, Y_1, R_1) \leftarrow (1, 0, a); (X_2, Y_2, R_2) \leftarrow (0, 1, b)$
2. if  $R_2 = 0$  then return  $R_1 = \gcd(a, b)$ ; no inverse
3. if  $R_2 = 1$  then return  $R_2 = \gcd(a, b); Y_2 = b^{-1} \pmod{a}$
4.  $Q = \lfloor R_1/R_2 \rfloor$
5.  $(X, Y, R) \leftarrow (X_1 - QX_2, Y_1 - QY_2, R_1 - QR_2)$
6.  $(X_1, Y_1, R_1) \leftarrow (X_2, Y_2, R_2)$
7.  $(X_2, Y_2, R_2) \leftarrow (X, Y, R)$
8. goto 2

 Invariants:  $aX_1 + bY_1 = R_1$  and  $aX_2 + bY_2 = R_2$ .

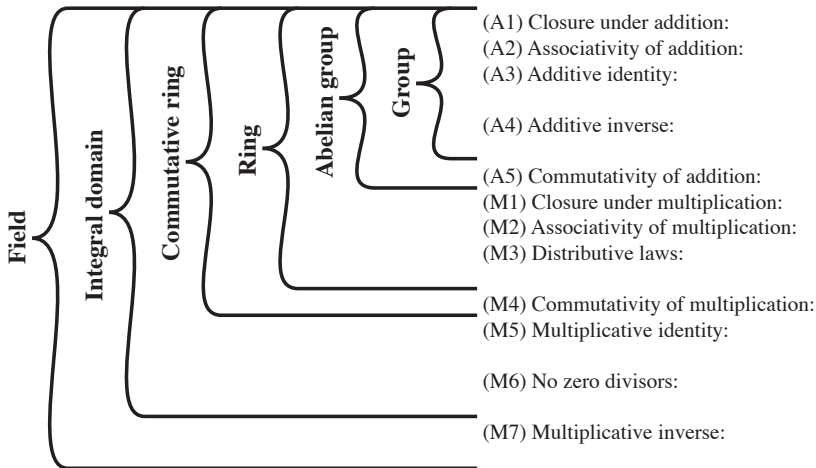
 If  $\gcd(a, b) = 1$ , then  $Y_2$  equals the multiplicative inverse of  $b$  modulo  $a$  when the algorithm terminates.

$$aX_2 + bY_2 = R_2 = 1 \rightarrow bY_2 = 1 - aX_2 \rightarrow bY_2 \equiv 1 \pmod{a}.$$



Source: Figure 4.2, Stallings 2010

# Groups, Rings, and Fields (cont.)



Source: Figure 4.2, Stallings 2010

# Groups, Rings, and Fields (cont.)

- (A1) Closure under addition: If  $a$  and  $b$  belong to  $S$ , then  $a + b$  is also in  $S$
- (A2) Associativity of addition:  $a + (b + c) = (a + b) + c$  for all  $a, b, c$  in  $S$
- (A3) Additive identity: There is an element  $0$  in  $R$  such that  $a + 0 = 0 + a = a$  for all  $a$  in  $S$
- (A4) Additive inverse: For each  $a$  in  $S$  there is an element  $-a$  in  $S$  such that  $a + (-a) = (-a) + a = 0$
- (A5) Commutativity of addition:  $a + b = b + a$  for all  $a, b$  in  $S$
- (M1) Closure under multiplication: If  $a$  and  $b$  belong to  $S$ , then  $ab$  is also in  $S$
- (M2) Associativity of multiplication:  $a(bc) = (ab)c$  for all  $a, b, c$  in  $S$
- (M3) Distributive laws:  $a(b + c) = ab + ac$  for all  $a, b, c$  in  $S$   
 $(a + b)c = ac + bc$  for all  $a, b, c$  in  $S$
- (M4) Commutativity of multiplication:  $ab = ba$  for all  $a, b$  in  $S$
- (M5) Multiplicative identity: There is an element  $1$  in  $S$  such that  $a1 = 1a = a$  for all  $a$  in  $S$
- (M6) No zero divisors: If  $a, b$  in  $S$  and  $ab = 0$ , then either  $a = 0$  or  $b = 0$
- (M7) Multiplicative inverse: If  $a$  belongs to  $S$  and  $a \neq 0$ , there is an element  $a^{-1}$  in  $S$  such that  $aa^{-1} = a^{-1}a = 1$

# Cyclic Groups

- Let  $a^n$  denote  $a \cdot a \cdot \dots \cdot a$  with  $n$  ( $\geq 0$ ) occurrences of  $a$ .  
Formally,

$$a^n = \begin{cases} e & \text{if } n = 0 \\ a \cdot a^{n-1} & \text{if } n > 0 \end{cases}$$

- A group  $G$  is *cyclic* if, for every  $b$  in  $G$ ,  $b = a^n$  for a **fixed**  $a$  in  $G$  and some integer  $n \geq 0$ .
- The fixed element  $a$  is said to *generate*  $G$  and is called the *generator* of  $G$ .



- Consider  $Z_p = \{0, 1, 2, \dots, (p - 1)\}$  where  $p$  is a prime.
- For each  $w \in Z_p$ ,  $w \neq 0$ , there exists a  $z \in Z_p$  such that  $w \times z \equiv 1 \pmod{p}$ .
- The element  $z$  is called the *multiplicative inverse* of  $w$ .
- For any prime  $p$ ,  $(Z_p, +, \times)$  is a *finite field of order  $p$* , denoted  $GF(p)$ .

# Arithmetic in $GF(7)$

+	0	1	2	3	4	5	6
0	0	1	2	3	4	5	6
1	1	2	3	4	5	6	0
2	2	3	4	5	6	0	1
3	3	4	5	6	0	1	2
4	4	5	6	0	1	2	3
5	5	6	0	1	2	3	4
6	6	0	1	2	3	4	5

(a) Addition modulo 7

×	0	1	2	3	4	5	6
0	0	0	0	0	0	0	0
1	0	1	2	3	4	5	6
2	0	2	4	6	1	3	5
3	0	3	6	2	5	1	4
4	0	4	1	5	2	6	3
5	0	5	3	1	6	4	2
6	0	6	5	4	3	2	1

(b) Multiplication modulo 7

	$w$	$-w$	$w^{-1}$
0	0	0	—
1	6	1	1
2	5	4	4
3	4	5	5
4	3	2	2
5	2	3	3
6	1	6	6

(c) Additive and multiplicative inverses modulo 7

Source: Table 4.5, Stallings 2010

# Polynomial Arithmetic

$$\begin{array}{r}
 x^3 + x^2 \quad + 2 \\
 + (x^2 - x + 1) \\
 \hline
 x^3 + 2x^2 - x + 3
 \end{array}$$

(a) Addition

$$\begin{array}{r}
 x^3 + x^2 \quad + 2 \\
 - (x^2 - x + 1) \\
 \hline
 x^3 \quad + x + 1
 \end{array}$$

(b) Subtraction

$$\begin{array}{r}
 x^3 + x^2 \quad + 2 \\
 \times (x^2 - x + 1) \\
 \hline
 x^3 + x^2 \quad + 2 \\
 - x^4 - x^3 \quad - 2x \\
 \hline
 x^5 + x^4 \quad + 2x^2 \\
 \hline
 x^5 \quad + 3x^2 - 2x + 2
 \end{array}$$

(c) Multiplication

$$\begin{array}{r}
 \phantom{x^2 - x + 1} \overline{) x^3 + x^2 \quad + 2} \\
 \underline{x^3 - x^2 + x} \phantom{+ 2} \\
 2x^2 - x + 2 \\
 \underline{2x^2 - 2x + 2} \\
 x
 \end{array}$$

(d) Division

Source: Figure 4.3, Stallings 2010

# Polynomial Arithmetic over $GF(2)$

$$\begin{array}{r}
 x^7 \quad + x^5 + x^4 + x^3 \quad + x + 1 \\
 \quad \quad \quad \quad \quad + (x^3 \quad + x + 1) \\
 \hline
 x^7 \quad + x^5 + x^4
 \end{array}$$

(a) Addition

$$\begin{array}{r}
 x^7 \quad + x^5 + x^4 + x^3 \quad + x + 1 \\
 \quad \quad \quad \quad \quad - (x^3 \quad + x + 1) \\
 \hline
 x^7 \quad + x^5 + x^4
 \end{array}$$

(b) Subtraction

Source: Figure 4.4, Stallings 2010

# Polynomial Arithmetic over $GF(2)$ (cont.)

$$\begin{array}{r}
 x^7 + x^5 + x^4 + x^3 + x + 1 \\
 \times (x^3 + x + 1) \\
 \hline
 x^7 + x^5 + x^4 + x^3 + x + 1 \\
 x^8 + x^6 + x^5 + x^4 + x^2 + x \\
 \hline
 x^{10} + x^8 + x^7 + x^6 + x^4 + x^3 \\
 \hline
 x^{10} + x^4 + x^2 + 1
 \end{array}$$

(c) Multiplication

$$\begin{array}{r}
 x^4 + 1 \\
 x^3 + x + 1 \overline{) x^7 + x^5 + x^4 + x^3 + x + 1} \\
 \underline{x^7 + x^5 + x^4} \phantom{+ x + 1} \\
 x^3 + x + 1 \\
 \underline{x^3 + x + 1} \\
 0
 \end{array}$$

(d) Division

Source: Figure 4.4, Stallings 2010

# Arithmetic in $GF(2^3)$

		000	001	010	011	100	101	110	111
	+	0	1	2	3	4	5	6	7
000	0	0	1	2	3	4	5	6	7
001	1	1	0	3	2	5	4	7	6
010	2	2	3	0	1	6	7	4	5
011	3	3	2	1	0	7	6	5	4
100	4	4	5	6	7	0	1	2	3
101	5	5	4	7	6	1	0	3	2
110	6	6	7	4	5	2	3	0	1
111	7	7	6	5	4	3	2	1	0

(a) Addition

		000	001	010	011	100	101	110	111
	×	0	1	2	3	4	5	6	7
000	0	0	0	0	0	0	0	0	0
001	1	0	1	2	3	4	5	6	7
010	2	0	2	4	6	3	1	7	5
011	3	0	3	6	5	7	4	1	2
100	4	0	4	3	7	6	2	5	1
101	5	0	5	1	4	2	7	3	6
110	6	0	6	7	1	5	3	2	4
111	7	0	7	5	2	1	6	4	3

(b) Multiplication

	$w$	$-w$	$w^{-1}$
0	0	—	—
1	1	1	1
2	2	2	5
3	3	3	6
4	4	4	7
5	5	5	2
6	6	6	3
7	7	7	4

(c) Additive and multiplicative inverses

# Modular Polynomial Arithmetic

- Let  $S$  denote the set of all polynomials of degree  $n - 1$  or less over the field  $Z_p$  with the form

$$f(x) = a_{n-1}x^{n-1} + a_{n-2}x^{n-2} + \cdots + a_1x + a_0$$

where each  $a_i$  takes on a value in  $Z_p$ . Arithmetic on the coefficients is performed modulo  $p$ .

- If multiplication results in a polynomial of degree greater than  $n - 1$ , then the polynomial is reduced modulo some **irreducible** polynomial of degree  $n$ .
- Each such  $S$  is a **finite field**; every nonzero element  $a$  in  $S$  has a multiplicative inverse  $a^{-1}$  such that  $a \times a^{-1} = 1$ .
- Such an  $S$  is denoted as **GF( $2^n$ )** when  $p = 2$ .

# Irreducible Polynomials

- 🌐 A polynomial  $f(x)$  is *irreducible* if  $f(x)$  cannot be expressed as a product of two polynomials with degrees lower than that of  $f(x)$ .
- 🌐 Irreducible polynomials play a role analogous to that of primes.
- 🌐 The AES algorithm uses the finite field  $\text{GF}(2^8)$  with the following irreducible polynomial modulus

$$x^8 + x^4 + x^3 + x + 1.$$



# Polynomial Arithmetic Modulo $(x^3 + x + 1)$

(a) Addition

		000	001	010	011	100	101	110	111
	+	0	1	$x$	$x+1$	$x^2$	$x^2+1$	$x^2+x$	$x^2+x+1$
000	0	0	1	$x$	$x+1$	$x^2$	$x^2+1$	$x^2+x$	$x^2+x+1$
001	1	1	0	$x+1$	$x$	$x^2+1$	$x^2$	$x^2+x+1$	$x^2+x$
010	$x$	$x$	$x+1$	0	1	$x^2+x$	$x^2+x+1$	$x^2$	$x^2+1$
011	$x+1$	$x+1$	$x$	1	0	$x^2+x+1$	$x^2+x$	$x^2+1$	$x^2$
100	$x^2$	$x^2$	$x^2+1$	$x^2+x$	$x^2+x+1$	0	1	$x$	$x+1$
101	$x^2+1$	$x^2+1$	$x^2$	$x^2+x+1$	$x^2+x$	1	0	$x+1$	$x$
110	$x^2+x$	$x^2+x$	$x^2+x+1$	$x^2$	$x^2+1$	$x$	$x+1$	0	1
111	$x^2+x+1$	$x^2+x+1$	$x^2+x$	$x^2+1$	$x^2$	$x+1$	$x$	1	0

(b) Multiplication

		000	001	010	011	100	101	110	111
	×	0	1	$x$	$x+1$	$x^2$	$x^2+1$	$x^2+x$	$x^2+x+1$
000	0	0	0	0	0	0	0	0	0
001	1	0	1	$x$	$x+1$	$x^2$	$x^2+1$	$x^2+x$	$x^2+x+1$
010	$x$	0	$x$	$x^2$	$x^2+x$	$x+1$	1	$x^2+x+1$	$x^2+1$
011	$x+1$	0	$x+1$	$x^2+x$	$x^2+1$	$x^2+x+1$	$x^2$	1	$x$
100	$x^2$	0	$x^2$	$x+1$	$x^2+x+1$	$x^2+x$	$x$	$x^2+1$	1
101	$x^2+1$	0	$x^2+1$	1	$x^2$	$x$	$x^2+x+1$	$x+1$	$x^2+x$
110	$x^2+x$	0	$x^2+x$	$x^2+x+1$	1	$x^2+1$	$x+1$	$x$	$x^2$
111	$x^2+x+1$	0	$x^2+x+1$	$x^2+1$	$x$	1	$x^2+x$	$x^2$	$x+1$

Source: Table 4.7, Stallings 2010

# Extended Euclid's Algorithm for $GF(p^n)$

*EXTENDED EUCLID*( $a(x), b(x)$ ) :

1.  $[V_1(x), W_1(x), R_1(x)] \leftarrow [1, 0, a(x)]; [V_2(x), W_2(x), R_2(x)] \leftarrow [0, 1, b(x)]$
2. if  $R_2(x) = 0$  then return  $R_1(x) = \gcd(a(x), b(x))$ ; no inverse
3. if  $R_2(x) = 1$  then return  $R_2(x) = \gcd(a(x), b(x)); W_2(x) = b^{-1}(x) \pmod{a(x)}$
4.  $Q(x) =$  the quotient of  $R_1(x)/R_2(x)$
5.  $[V(x), W(x), R(x)]$   
 $\leftarrow [V_1(x) - Q(x)V_2(x), W_1(x) - Q(x)W_2(x), R_1(x) - Q(x)R_2(x)]$
6.  $[V_1(x), W_1(x), R_1(x)] \leftarrow [V_2(x), W_2(x), R_2(x)]$
7.  $[V_2(x), W_2(x), R_2(x)] \leftarrow [V(x), W(x), R(x)]$
8. goto 2

- 🌐 Invariants:  $a(x)V_1(x) + b(x)W_1(x) = R_1(x)$  and  $a(x)V_2(x) + b(x)W_2(x) = R_2(x)$ .
- 🌐 If  $\gcd(a(x), b(x)) = 1$ , then  $W_2(x)$  equals the multiplicative inverse of  $b(x)$  modulo  $a(x)$  when the algorithm terminates.

# A Run of Extended Euclid

The following run finds the multiplicative inverse of  $x^7 + x + 1$  in  $GF(2^8)$  with  $x^8 + x^4 + x^3 + x + 1$  as the irreducible polynomial modulus; the result is  $x^7$ .

<b>Initialization</b>	$a(x) = x^8 + x^4 + x^3 + x + 1; v_{-1}(x) = 1; w_{-1}(x) = 0$ $b(x) = x^7 + x + 1; v_0(x) = 0; w_0(x) = 1$
<b>Iteration 1</b>	$q_1(x) = x; r_1(x) = x^4 + x^3 + x^2 + 1$ $v_1(x) = 1; w_1(x) = x$
<b>Iteration 2</b>	$q_2(x) = x^3 + x^2 + 1; r_2(x) = x$ $v_2(x) = x^3 + x^2 + 1; w_2(x) = x^4 + x^3 + x + 1$
<b>Iteration 3</b>	$q_3(x) = x^3 + x^2 + x; r_3(x) = 1$ $v_3(x) = x^6 + x^2 + x + 1; w_3(x) = x^7$
<b>Iteration 4</b>	$q_4(x) = x; r_4(x) = 0$ $v_4(x) = x^7 + x + 1; w_4(x) = x^8 + x^4 + x^3 + x + 1$
<b>Result</b>	$d(x) = r_3(x) = \gcd(a(x), b(x)) = 1$ $w(x) = w_3(x) = (x^7 + x + 1)^{-1} \bmod (x^8 + x^4 + x^3 + x + 1) = x^7$

Source: Table 4.8, Stallings 2010

# Bytes and Polynomials in $\text{GF}(2^8)$

- 🌐 In the AES algorithm, the basic unit for processing is a **byte**.
- 🌐 A byte  $b_7b_6b_5b_4b_3b_2b_1b_0$  is interpreted as an element of the finite field  $\text{GF}(2^8)$  using the polynomial representation:

$$b_7x^7 + b_6x^6 + b_5x^5 + b_4x^4 + b_3x^3 + b_2x^2 + b_1x + b_0 = \sum_{i=0}^7 b_i x^i.$$

- 🌐 For example, 01100011 identifies  $x^6 + x^5 + x + 1$ .

# Addition in $GF(2^8)$

- 🌐 The addition of two polynomials in the finite field  $GF(2^8)$  is achieved by adding (modulo 2) the coefficients of the corresponding powers.

polynomial representation:

$$(x^6 + x^4 + x^2 + x + 1) + (x^7 + x + 1) = x^7 + x^6 + x^4 + x^2$$

binary representation:

$$01010111 \oplus 10000011 = 11010100$$

hexadecimal representation:

$$\{57\} \oplus \{83\} = \{D4\}$$

# Multiplication in $GF(2^8)$

- Let  $f(x)$  be  $b_7x^7 + b_6x^6 + b_5x^5 + b_4x^4 + b_3x^3 + b_2x^2 + b_1x + b_0$ .
- Multiply  $f(x)$  by  $x$ , we have

$$\begin{aligned} & f(x) \times x \\ = & b_7x^8 + b_6x^7 + b_5x^6 + b_4x^5 + b_3x^4 + b_2x^3 + b_1x^2 + b_0x \\ & \text{mod } m(x) \end{aligned}$$

Again, for the AES algorithm,

$$m(x) = x^8 + x^4 + x^3 + x + 1.$$

- When  $b_7 = 0$ , the result is already in the reduced form.

# Multiplication in $\text{GF}(2^8)$ (cont.)

🌐 When  $b_7 = 1$ :

$$\begin{aligned}
 & f(x) \times x \\
 = & (x^7 + b_6x^6 + b_5x^5 + b_4x^4 + b_3x^3 + b_2x^2 + b_1x + b_0) \times x \pmod{m(x)} \\
 = & x^8 + b_6x^7 + b_5x^6 + b_4x^5 + b_3x^4 + b_2x^3 + b_1x^2 + b_0x \pmod{m(x)} \\
 = & (b_6x^7 + b_5x^6 + b_4x^5 + b_3x^4 + b_2x^3 + b_1x^2 + b_0x) + \\
 & (x^4 + x^3 + x + 1) \pmod{m(x)}
 \end{aligned}$$

Note:  $x^8 \pmod{m(x)} = m(x) - x^8 = x^4 + x^3 + x + 1$ .

🌐 To summarize in binary representation,

$$f(x) \times x = \begin{cases} (b_6b_5b_4b_3b_2b_1b_00) & \text{if } b_7 = 0 \\ (b_6b_5b_4b_3b_2b_1b_00) \oplus (00011011) & \text{if } b_7 = 1 \end{cases}$$

🌐 Repeat the above to get multiplications by  $x^2$ ,  $x^3$ , etc.

# Generators for Finite Fields

A generator for  $GF(2^3)$  using  $f(x) = x^3 + x + 1$  (irreducible):

Power Representation	Polynomial Representation	Binary Representation	Decimal (Hex) Representation
0	0	000	0
$g^0 (= g^7)$	1	001	1
$g^1$	$g$	010	2
$g^2$	$g^2$	100	4
$g^3$	$g + 1$	011	3
$g^4$	$g^2 + g$	110	6
$g^5$	$g^2 + g + 1$	111	7
$g^6$	$g^2 + 1$	101	5

Source: Table 4.9, Stallings 2010

Note:  $f(g) = g^3 + g + 1 = 0$ ,  $g^3 = -g - 1 = g + 1$ ,  
 $g^4 = g(g^3) = g(g + 1) = g^2 + g$ , etc.



# GF(2<sup>3</sup>) Arithmetic Using a Generator

(a) Addition

	000	001	010	100	011	110	111	101
	0	1	$G$	$g^2$	$g^3$	$g^4$	$g^5$	$g^6$
000	0	1	$G$	$g^2$	$g+1$	$g^2+g$	$g^2+g+1$	$g^2+1$
001	1	0	$g+1$	$g^2+1$	$g$	$g^2+g+1$	$g^2+g$	$g^2$
010	$g$	$g+1$	0	$g^2+g$	1	$g^2$	$g^2+1$	$g^2+g+1$
100	$g^2$	$g^2+1$	$g^2+g$	0	$g^2+g+1$	$g$	$g+1$	1
011	$g+1$	$g$	1	$g^2+g+1$	0	$g^2+1$	$g^2$	$g^2+g$
110	$g^2+g$	$g^2+g+1$	$g^2$	$g$	$g^2+1$	0	1	$g+1$
111	$g^2+g+1$	$g^2+g$	$g^2+1$	$g+1$	$g^2$	1	0	$g$
101	$g^2+1$	$g^2$	$g^2+g+1$	1	$g^2+g$	$g+1$	$g$	0

(b) Multiplication

	000	001	010	100	011	110	111	101
	0	1	$G$	$g^2$	$g^3$	$g^4$	$g^5$	$g^6$
000	0	0	0	0	0	0	0	0
001	0	1	$G$	$g^2$	$g+1$	$g^2+g$	$g^2+g+1$	$g^2+1$
010	$g$	$g$	$g^2$	$g+1$	$g^2+g$	$g^2+g+1$	$g^2+1$	1
100	$g^2$	$g^2$	$g+1$	$g^2+g$	$g^2+g+1$	$g^2+1$	1	$g$
011	$g^3$	$g+1$	$g^2+g$	$g^2+g+1$	$g^2+1$	1	$g$	$g^2$
110	$g^4$	$g^2+g$	$g^2+g+1$	$g^2+1$	1	$g$	$g^2$	$g+1$
111	$g^5$	$g^2+g+1$	$g^2+1$	1	$g$	$g^2$	$g+1$	$g^2+g$
101	$g^6$	$g^2+1$	1	$g$	$g^2$	$g+1$	$g^2+g$	$g^2+g+1$

Source: Table 4.10, Stallings 2010