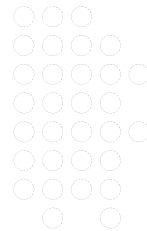


Euclidean Algorithm for GCD and Extended Euclidean Algorithm for the Inverse of an Element in Z_n^*

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Greatest Common Divisor

- Euclidean Algorithm: calculating GCD

gcd(1180, 482)

(輾轉相除法)

2	482 432	1180 964	2
3	50 48	216 200	4
	2	16 16	8
		0	

Greatest Common Divisor (cont'd)

- GCD of a and b is the largest positive integer divides both a and b
- gcd(a, b) or (a,b)
- ex. gcd(6, 4) = 2, gcd(5, 7) = 1
- Euclidean algorithm

- ex. gcd(482, 1180)

$$\begin{aligned}
 1180 &= 2 \cdot 482 + 216 \\
 482 &= 2 \cdot 216 + 50 \\
 216 &= 4 \cdot 50 + 16 \\
 50 &= 3 \cdot 16 + 2 \\
 16 &= 8 \cdot 2 + 0
 \end{aligned}$$

← gcd

remainder → divisor → dividend → ignore

Why does it work?

Let $d = \text{gcd}(482, 1180)$
 $d \mid 482$ and $d \mid 1180 \Rightarrow d \mid 216$
 because $216 = 1180 - 2 \cdot 482$
 $d \mid 216$ and $d \mid 482 \Rightarrow d \mid 50$
 $d \mid 50$ and $d \mid 216 \Rightarrow d \mid 16$
 $d \mid 16$ and $d \mid 50 \Rightarrow d \mid 2$
 $2 \mid 16 \Rightarrow d = 2$

Iterated C Program Design

- 將變數 p 設為變數 n1 內容的絕對值, 將變數 q 設為變數 n2 內容的絕對值

- 將 p 除以 q 的餘數設為 r

- 當 r 大於 0 時

3.1 拷貝 q 的數值至 p

3.2 拷貝 r 的數值至 q

3.3 將 p 除以 q 的餘數設為 r

- q 即為 n1 和 n2 的最大公因數

```

int find_gcd(int n1, int n2) {
    int p, q, r;
    p = abs(n1);
    q = abs(n2);
    r = p % q;
    while (r != 0) {
        p = q;
        q = r;
        r = p % q;
    }
    return q;
}
    
```

Recursive Solution

```

01 int gcd(int p, int q) // assume p >= q
02 {
03     int ans;
04
05     if (p % q == 0)
06         ans = q;
07     else
08         ans = gcd(q, p % q);
09
10     return ans;
11 }

```

```

01 int gcd(int p, int q)
02 {
03     int r = p%q;
04     if (r == 0)
05         return q;
06     return gcd(q, r);
07 }

```

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Integer Multiplicative Group Z_p^*

- A group G is a finite or infinite set of elements and a binary operation \times which together satisfy

- Closure: $\forall a, b \in G \quad a \times b = c \in G$ 封閉性
- Associativity: $\forall a, b, c \in G \quad (a \times b) \times c = a \times (b \times c)$ 結合性
- Identity: $\forall a \in G \quad 1 \times a = a \times 1 = a$ 單位元素
- Inverse: $\forall a \in G \quad a \times a^{-1} = 1 = a^{-1} \times a$ 反元素

- e.g. $p=11, Z_{11}^* = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$
binary operation: $\times \pmod{p}$, identity: 1, inverse: x^{-1} can be found using the "extended Euclidean Algorithm"

$1 * 1 \equiv 1 \pmod{11}$	$6 * 2 = 12 \equiv 1 \pmod{11}$
$2 * 6 = 12 \equiv 1 \pmod{11}$	$7 * 8 = 56 \equiv 1 \pmod{11}$
$3 * 4 = 12 \equiv 1 \pmod{11}$	$8 * 7 = 56 \equiv 1 \pmod{11}$
$4 * 3 = 12 \equiv 1 \pmod{11}$	$9 * 5 = 45 \equiv 1 \pmod{11}$
$5 * 9 = 45 \equiv 1 \pmod{11}$	$10 * 10 = 100 \equiv 1 \pmod{11}$

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Extended Euclidean algorithm for finding the inverse in Z_p^*

- Def: a and b are relatively prime: $\gcd(a, b) = 1$
- Theorem: Let a and b be two nonzero integers, and let $d = \gcd(a, b)$. Then there exist integers x, y such that $a \cdot x + b \cdot y = d$
 - Constructive proof: Use the following Extended Euclidean Algorithm to find x and y

$$\begin{aligned}
 d = 2 &= 50 - 3 \cdot 16 && 216 = 1180 - 2 \cdot 482 \\
 &= (482 - 2 \cdot 216) - 3 \cdot (216 - 4 \cdot 50) && 50 = 482 - 2 \cdot 216 \\
 &= \dots = 1180 \cdot (-29) + 482 \cdot 71 && 16 = 216 - 4 \cdot 50
 \end{aligned}$$

$\begin{matrix} \nearrow & \nearrow & \nearrow \\ a & x & b & y \end{matrix}$

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Extended Euclidean Algorithm

Let $\gcd(a, b) = d$

- Looking for s and t , $\gcd(s, t) = 1$ s.t. $a \cdot s + b \cdot t = d$
- When $d = 1$, $t \equiv b^{-1} \pmod{a}$

Ex. $1180 = 2 \cdot 482 + 216$

$$\begin{aligned}
 1180 - 2 \cdot 482 &= 216 \\
 482 &= 2 \cdot 216 + 50 \\
 482 - 2 \cdot (1180 - 2 \cdot 482) &= 50 \\
 -2 \cdot 1180 + 5 \cdot 482 &= 50 \\
 216 &= 4 \cdot 50 + 16 \\
 (1180 - 2 \cdot 482) - & \\
 4 \cdot (-2 \cdot 1180 + 5 \cdot 482) &= 16 \\
 9 \cdot 1180 - 22 \cdot 482 &= 16 \\
 50 &= 3 \cdot 16 + 2 \\
 (-2 \cdot 1180 + 5 \cdot 482) - & \\
 3 \cdot (9 \cdot 1180 - 22 \cdot 482) &= 2 \\
 -29 \cdot 1180 + 71 \cdot 482 &= 2
 \end{aligned}$$

write r_1, r_2, \dots, d as linear combination of a and b

$$\begin{aligned}
 a &= q_1 \cdot b + r_1 && \textcircled{1} \\
 b &= q_2 \cdot r_1 + r_2 && \textcircled{2} \\
 r_1 &= q_3 \cdot r_2 + r_3 && \textcircled{3} \\
 r_2 &= q_4 \cdot r_3 + d && \textcircled{4} \\
 r_3 &= q_5 \cdot d + 0 && \textcircled{5}
 \end{aligned}$$

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Derive the Iteration Formula

- in the forward direction, let $r_0 = a$, $r_1 = b$, $\gcd(a,b) = 1$

$$r_0 = a_0 r_0 + b_0 r_1$$

$$r_1 = a_1 r_0 + b_1 r_1$$

$$r_0 = q_0 r_1 + r_2 \quad r_0 - q_0 r_1 = r_2 = a_2 r_0 + b_2 r_1$$

$$r_1 = q_1 r_2 + r_3 \quad r_1 - q_1 r_2 = r_3 = a_3 r_0 + b_3 r_1$$

$$r_2 = q_2 r_3 + r_4 \quad r_2 - q_2 r_3 = r_4 = a_4 r_0 + b_4 r_1$$

...

...

$$r_{i-2} - q_{i-2} r_{i-1} = r_i = a_i r_0 + b_i r_1$$

$$\begin{cases} a_i = a_{i-2} - q_{i-2} a_{i-1} \\ b_i = b_{i-2} - q_{i-2} b_{i-1} \end{cases}$$

where $a_0 = 1$, $b_0 = 0$, $a_1 = 0$, $b_1 = 1$

if $r_i == 0$ then $r_{i-1} = 1$

$$a_{i-1} r_0 + b_{i-1} r_1 = r_{i-1} = 1$$

i.e. $a_{i-1} r_0 \equiv 1 \pmod{r_1}$

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Implementation (w/o using array)

```
int x, p, r, a, am1=0, am2=1;
int b, bm1=1, bm2=0, q, qm1, qm2;

printf("Please input (x, p), where "
      "gcd(x,p)=1 > "); /* assume p >=x */
scanf("%d %d", &x, &p);
printf("inverse(%d) (mod %d) = ", x, p);

if (x == 1) printf("%d\n", x), return 0;

qm2 = p / x; r = p % x; p = x; x = r;
qm1 = p / x; r = p % x; p = x; x = r;

a = am2 - qm2 * am1;
b = bm2 - qm2 * bm1;
```

```
while (r != 0)
{
    q = p / x;
    r = p % x;

    p = x;
    x = r;
    am2 = am1; am1 = a;
    bm2 = bm1; bm1 = b;
    qm2 = qm1; qm1 = q;
    a = am2 - qm2 * am1;
    b = bm2 - qm2 * bm1;
}
printf("%d\n", b);
```

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Another Implementation

```
01 int main(void) {
02     int x, y, a, b;
03     int quotient[50], nIter, gcd;
04     printf("Please input two integers > ");
05     scanf("%d%d", &x, &y);
06     gcd = euclidean(&x, &y, &nIter, quotient);
07     printf("gcd(%d, %d) = %d\n", x, y, gcd);
08     extendedEuclidean(quotient, nIter, &a, &b);
09     if (x < 0) a = -a;
10     if (y < 0) b = -b;
11     prettyPrint(gcd, a, x, b, y);
12     system("pause");
13     return 0;
14 }
```

using Array

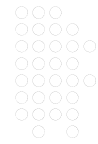
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Euclidean Algorithm

```
01 int euclidean(int *x, int *y, int *nIter, int quotient[ ]) {
02     int divisor, remainder, dividant, iter=0;
03     if (*x < *y) swap(x, y);
04     dividant = *x < 0 ? -(*x) : *x;
05     divisor = *y < 0 ? -(*y) : *y;
06     do
07     {
08         quotient[iter++] = dividant / divisor;
09         remainder = dividant % divisor;
10         dividant = divisor;
11         divisor = remainder;
12     } while (remainder != 0);
13     *nIter = iter;
14     return dividant;
15 }
```

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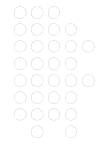
Extended Euclidean Algorithm



```
01 void extendedEuclidean(int q[], int nIter, int *a, int *b) {
02     int a1[3] = {1, 0, -1}, b1[3] = {0, 1, -1}, i;
03     for (i=0; i<nIter-1; i++) {
04         a1[2] = a1[0] - q[i] * a1[1];
05         b1[2] = b1[0] - q[i] * b1[1];
06         a1[0] = a1[1];
07         a1[1] = a1[2];
08         b1[0] = b1[1];
09         b1[1] = b1[2];
10     }
11     *a = a1[1];
12     *b = b1[1];
13 }
```

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Recursive Solution



- Given $a > b \geq 0$, find $g = \text{GCD}(a, b)$ and x, y s.t. $a x + b y = g$ where $|x| \leq b+1$ and $|y| \leq a+1$
- Let $a = q b + r, b > r \geq 0 \Rightarrow (q b + r) x + b y = g$
 $\Rightarrow b (q x + y) + r x = g$
 $\Rightarrow b y' + r x = g$, where $y' = q x + y$
- This means that if we can find y' and x satisfying $b y' + (a \% b) x = g$ then x and $y = y' - q x = y' - (a/b) x$ satisfies $a x + b y = g$
Note that in this way r will eventually be 0

```
01 void extgcd(int a, int b, int *g, int *x, int *y) { // a > b >= 0
02     if (b == 0)
03         *g = a, *x = 1, *y = 0;
04     else {
05         extgcd(b, a % b, g, y, x);
06         *y = *y - (a/b) * (*x);
07     }
08 }
```

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