

Number-Theoretic Algorithms

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Number-Theoretic Algorithms

- 1 Modular Arithmetic
- 2 Euclid's Algorithm
- 3 Pairwise Relatively Prime
- 4 Chinese Remainder Theorem

Cancellation in modular arithmetic

(TC 31.4.2)

$$ad \equiv bd \pmod{n} \not\Rightarrow a \equiv b \pmod{n}$$

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$$3 \cdot 2 \equiv 5 \cdot 2 \pmod{4} \quad 3 \not\equiv 5 \pmod{4}$$

Cancellation in modular arithmetic

(TC 31.4.2)

$$ad \equiv bd \pmod{n} \not\Rightarrow a \equiv b \pmod{n}$$

$$ad \equiv bd \pmod{n}, a \perp n \Rightarrow a \equiv b \pmod{n}$$

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Changing the modulus

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Changing the modulus

$$n = n_1 n_2 \cdots n_k$$

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$$a \equiv b \pmod{100} \implies a \equiv b \pmod{20} \implies a \equiv b \pmod{5}$$

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$$\forall 1 \leq i \leq k, a \equiv b \pmod{n_i} \iff a \equiv b \pmod{n}, \text{ if } n_i \perp n_j$$

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Worst-case analysis of Euclid's algorithm

(TC 31.2–5)

1. If $a > b \geq 0$, $\text{EUCLID}(a, b)$ makes $\leq r \triangleq 1 + \log_{\phi} b$ recursive calls.

$$a > b \geq 1, b < F_{k+1} \implies r < k.$$

$$r \leq 1 + \log_{\phi} b \implies k = 2 + \log_{\phi} b, b < F_{3+\log_{\phi} b}$$

$$F_k = \frac{\phi^k - \hat{\phi}^k}{\sqrt{5}} = \left\lfloor \frac{\phi^k}{\sqrt{5}} \right\rfloor \geq \frac{\phi^k}{\sqrt{5}}$$

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$$(16, 12)$$

$$= (12, 4)$$

$$= (4, 0)$$

$$= 4$$

$$(4, 3)$$

$$= (3, 1)$$

$$= (1, 0)$$

$$= 1$$

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$$(a, b) = (a, b) \cdot \left(\frac{a}{(a, b)}, \frac{b}{(a, b)} \right)$$

$$\begin{array}{ll}
 (16, 12) & (4, 3) \\
 = (12, 4) & = (3, 1) \\
 = (4, 0) & = (1, 0) \\
 = 4 & = 1 \\
 \text{EUCLID}(a, b) \leftrightarrow \text{EUCLID}\left(\frac{a}{(a, b)}, \frac{b}{(a, b)}\right)
 \end{array}$$

Worst-case analysis of Euclid's algorithm

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$$\text{EUCLID}(a, b) \leftrightarrow \text{EUCLID}\left(\frac{a}{(a, b)}, \frac{b}{(a, b)}\right)$$

$$\text{EUCLID}(b, a \bmod b) \leftrightarrow \text{EUCLID}\left(\frac{b}{(a, b)}, \frac{a}{(a, b)} \bmod \frac{b}{(a, b)}\right)$$

$$\frac{a}{(a, b)} \bmod \frac{b}{(a, b)} = \frac{a \bmod b}{(a, b)}$$

Worst-case analysis of Euclid's algorithm

(TC 31.2–5)

2. Improve this bound to $1 + \log_{\phi}\left(\frac{b}{(a,b)}\right)$.

Lemma (Generalization of Lemma 31.10)

If $a > b \geq 1$, $d = (a, b)$ and $\text{EUCLID}(a, b)$ performs $k \geq 1$ recursive calls, then $a \geq dF_{k+2}$ and $b \geq dF_{k+1}$.

Average-case analysis of Euclid's algorithm

$$T(m, 0) = 0; \quad T(m, n) = 1 + T(n, m \bmod n) \quad n \geq 1$$

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$$T_n \approx 1 + \frac{1}{n}(T_0 + T_1 + \cdots + T_{n-1})$$

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$$T_n \approx 1 + \frac{1}{n}(T_0 + T_1 + \cdots + T_{n-1}) = 1 + \frac{1}{2} + \cdots + \frac{1}{n} = H_n \approx \ln n + O(1)$$

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Reference

“The Art of Computer Programming, Vol 2: Seminumerical Algorithms (Section 4.5.3)” by Donald E. Knuth, 3rd edition.

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Pairwise relatively prime

(TC 31.2–9)

n_1, n_2, n_3, n_4 are pairwise relatively prime

\Longleftrightarrow

$$\gcd(n_1 n_2, n_3 n_4) = \gcd(n_1 n_3, n_2 n_4) = 1$$

Pairwise relatively prime

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a set of $\lceil \lg k \rceil$ pairs of numbers derived from the n_i are relatively prime.

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$$\binom{k}{2} = \Theta(k^2) \quad (\text{complete graph})$$

$$\gcd(\boxed{1_L}, \boxed{1_R}) = \gcd(\boxed{2_L}, \boxed{2_R}) = \dots = \gcd(\boxed{\lceil \lg k \rceil_L}, \boxed{\lceil \lg k \rceil_R}) = 1$$

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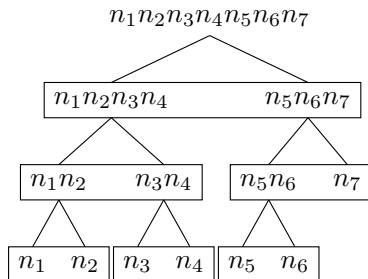
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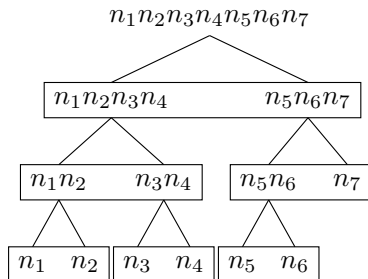
$$k = 3 : \quad \gcd(n_1, n_2 n_3) = \gcd(n_2, n_3) = 1$$

$$k = 2 : \quad \gcd(n_1, n_2) = 1$$

Pairwise relatively prime: divide-and-conquer

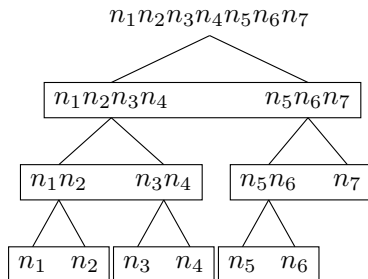


Pairwise relatively prime: divide-and-conquer



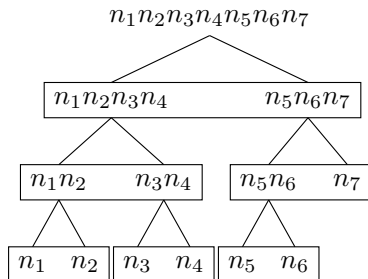
$$\begin{cases} T(1) = 0 \\ T(k) = 2T(\frac{k}{2}) + 1 \end{cases}$$

Pairwise relatively prime: divide-and-conquer



$$\begin{cases} T(1) = 0 \\ T(k) = 2T(\frac{k}{2}) + 1 \end{cases} \implies T(k) = k - 1$$

Pairwise relatively prime: divide-and-conquer



$$\begin{cases} T(1) = 0 \\ T(k) = 2T(\frac{k}{2}) + 1 \end{cases} \implies T(k) = k - 1$$

$$T_k = k - 1 : (n_i, n_{i+1}n_{i+2} \cdots n_k) \quad \forall 1 \leq i < k$$

Pairwise relatively prime: smarter combination

$$\begin{cases} T(1) = 0 \\ T(k) = T(\frac{k}{2}) + 1 \end{cases}$$

Pairwise relatively prime: smarter combination

$$\begin{cases} T(1) = 0 \\ T(k) = T(\frac{k}{2}) + 1 \end{cases} \implies T(k) = \lceil \lg k \rceil$$

Pairwise relatively prime: the dividing pattern

$$k = 7 : \quad n_0, n_1, n_2, \dots, n_6$$

000

001

010

011

100

101

110

Pairwise relatively prime: the dividing pattern

$$k = 7: \quad n_0, n_1, n_2, \dots, n_6$$

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$$T(k) = \lceil \lg k \rceil$$

Can we do even better?

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Prove by (strong) mathematical induction.

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Prove by (strong) mathematical induction.

$$\begin{aligned} T(k) &\geq 1 + T(\lceil \frac{k}{2} \rceil) \\ &\geq 1 + \lceil \lg \lceil \frac{k}{2} \rceil \rceil \\ &= \lceil \lg k \rceil \end{aligned}$$

Biclique covering

Covering a complete graph with few complete bipartite subgraphs.

covering a graph by complete bipartite graphs

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 Abstract. We consider computational problems on covering graphs with bicliques (complete bipartite subgraphs). Given a graph and an integer k , the biclique ...

Biclique covering: rethinking the first divide-and-conquer

$$T(k) = k - 1$$

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$$T(k) = k - 1$$

edge-disjoint biclique partition

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Reference for $T(k) \geq k - 1$

“On the Addressing Problem for Loop Switching” by Graham and Pollak, 1971.

Biclique covering: rethinking the first divide-and-conquer

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edge-disjoint biclique partition

Reference for $T(k) \geq k - 1$

“On the Addressing Problem for Loop Switching” by Graham and Pollak, 1971.

Reference for *weighted* biclique partition

“Covering a Graph by Complete Bipartite Graphs” by P. Erdős and L. Pyber, 1997.

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Chinese Remainder Theorem (CRT)

Theorem (CRT)

$$n_1, \dots, n_k; \quad a_1, \dots, a_k$$

$$n_i \perp n_j \quad i \neq j, \quad n = n_1 n_2 \cdots n_k$$

$$\exists! a \ (0 \leq a < n) : a \equiv a_i \pmod{n_i}.$$

Chinese Remainder Theorem (CRT)

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$$a \leftrightarrow (a_1, a_2, \dots, a_k)$$

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$$a \leftrightarrow (a_1, a_2, \dots, a_k)$$

Proof for uniqueness.

$$a \equiv a' \pmod{n_i} \implies n \mid a - a'.$$



History of CRT

Proof of CRT (1)

Nonconstructive proof.

$$f : [0, n) \rightarrow \prod_{1 \leq i \leq k} [0, a_i)$$

$$f : a \mapsto (a \bmod n_1, \dots, a \bmod n_k)$$

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► f is one-to-one.



Proof of CRT (1)

Nonconstructive proof.

$$f : [0, n) \rightarrow \prod_{1 \leq i \leq k} [0, a_i)$$

$$f : a \mapsto (a \bmod n_1, \dots, a \bmod n_k)$$

- ▶ f is one-to-one.
- ▶ f is onto.

$$\exists a : f(a) = (a_1, \dots, a_k).$$



Proof of CRT (2)

Constructive proof by induction.

$$a \equiv a_1 \pmod{n_1} \tag{1}$$

$$a \equiv a_2 \pmod{n_2} \tag{2}$$

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$$(1) \implies a = a_1 + n_1 y$$

Proof of CRT (2)

Constructive proof by induction.

$$a \equiv a_1 \pmod{n_1} \quad (1)$$

$$a \equiv a_2 \pmod{n_2} \quad (2)$$

$$(1) \implies a = a_1 + n_1 y$$

$$x = a_1 + n_1 n_1^{-1} (a_2 - a_1) \pmod{n_1 n_2}$$



Proof of CRT (3)

Constructive proof by induction.

$$a \equiv a_1 \pmod{n_1} \tag{3}$$

$$a \equiv a_2 \pmod{n_2} \tag{4}$$

$$n_1 \perp n_2 \implies n_1 n'_1 + n_2 n'_2 = 1$$

Proof of CRT (3)

Constructive proof by induction.

$$a \equiv a_1 \pmod{n_1} \quad (3)$$

$$a \equiv a_2 \pmod{n_2} \quad (4)$$

$$n_1 \perp n_2 \implies n_1 n'_1 + n_2 n'_2 = 1$$

$$x = a_1 n_1 n'_1 + a_2 n_2 n'_2 \pmod{n_1 n_2}$$



Proof of CRT (4)

Constructive proof.

1. $x \equiv 1 \pmod{n_i}, \quad x \equiv 0 \pmod{n_j} \quad (i \neq j)$

$$x = M_i(M_i^{-1} \bmod n_i) \implies x = M_i M_i^{-1} \pmod{n}$$



Proof of CRT (4)

Constructive proof.

$$1. \quad x \equiv 1 \pmod{n_i}, \quad x \equiv 0 \pmod{n_j} \quad (i \neq j)$$

$$x = M_i(M_i^{-1} \bmod n_i) \implies x = M_i M_i^{-1} \pmod{n}$$

$$2. \quad x \equiv a_i \pmod{n_i}, \quad x \equiv 0 \pmod{n_j} \quad (i \neq j)$$

$$x = a_i M_i M_i^{-1} \pmod{n}$$



Proof of CRT (4)

Constructive proof.

$$1. \ x \equiv 1 \pmod{n_i}, \quad x \equiv 0 \pmod{n_j} \ (i \neq j)$$

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$$2. \ x \equiv a_i \pmod{n_i}, \quad x \equiv 0 \pmod{n_j} \ (i \neq j)$$

$$x = a_i M_i M_i^{-1} \pmod{n}$$

$$3. \ a \equiv a_i \pmod{n_i}, \forall 1 \leq i \leq k$$

$$a = \sum_{1 \leq i \leq k} a_i M_i M_i^{-1} \pmod{n}$$



Proof of CRT (5)

More efficient constructive proof.

Reference

“The Residue Number System” by Garner, 1959.

Reference

“The Art of Computer Programming, Vol 2: Seminumerical Algorithms (Section 4.3.2)” by Donald E. Knuth, 3rd edition.



Operations over CRT

$$a \leftrightarrow (a_1, a_2, \dots, a_n)$$

$$a \pm b \leftrightarrow (a_1 \pm b_1, a_2 \pm b_2, \dots, a_n \pm b_n)$$

$$a \times b \leftrightarrow (a_1 \times b_1, a_2 \times b_2, \dots, a_n \times b_n)$$

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TC 31.5–3

$$a \leftrightarrow (a_1, a_2, \dots, a_n), (a, n) = 1 \implies a^{-1} \leftrightarrow (a_1^{-1}, a_2^{-1}, \dots, a_n^{-1})$$

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Proof.

$$a^{-1} \equiv a_i^{-1} \pmod{n_i}$$

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$$a \leftrightarrow (a_1, a_2, \dots, a_n), (a, n) = 1 \implies a^{-1} \leftrightarrow (a_1^{-1}, a_2^{-1}, \dots, a_n^{-1})$$

Proof.

$$a^{-1} \equiv a_i^{-1} \pmod{n_i} \iff \begin{cases} a \equiv a_i \pmod{n_i} \\ (a, n) = 1 \end{cases}$$



The ϕ function

Theorem (The ϕ function)

$$\begin{aligned}\phi(p) &= p - 1 \\ \phi(p^k) &= p^k - p^{k-1}\end{aligned}$$

The ϕ function

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$$\begin{aligned}\phi(p) &= p - 1 \\ \phi(p^k) &= p^k - p^{k-1}\end{aligned}$$

$$\phi(n) = n \prod_{i=1}^r \left(1 - \frac{1}{p_i}\right) \quad \left(n = \prod_{i=1}^r p_i^{k_i}\right)$$

The ϕ function

Theorem (The ϕ function)

$$\begin{aligned}\phi(p) &= p - 1 \\ \phi(p^k) &= p^k - p^{k-1}\end{aligned}$$

$$\phi(n) = n \prod_{i=1}^r \left(1 - \frac{1}{p_i}\right) \quad \left(n = \prod_{i=1}^r p_i^{k_i}\right)$$

“We shall not prove this formula here.” — CLRS (Section 31.3)

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Proof.

$$U_{mn} = \{a \bmod mn, (a, mn) = 1\}$$

$$U_m = \{b \bmod m, (b, m) = 1\} \quad U_n = \{c \bmod n, (c, n) = 1\}$$

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$$f : U_{mn} \rightarrow U_m \times U_n$$

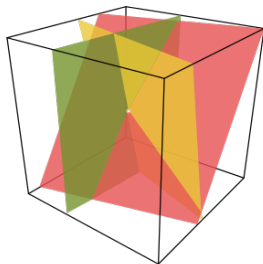
$$f(a \bmod mn) = (a \bmod m, a \bmod n).$$



Secret sharing using the CRT

Definition ($((k, n)$ -threshold secret sharing scheme)

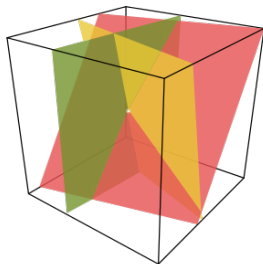
$(2, 3)$ -secret sharing:



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Reference

“How to Share a Secret” by Maurice Mignotte, 1982.

Secret sharing using the CRT

1. Choose m_i :

$$m_1 < m_2 < \cdots < m_n, \quad m_i \perp m_j, \quad \prod_{i=n-k+2}^n m_i < \prod_{i=1}^k m_i$$

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3. Compute the shares:

$$s_i = S \bmod m_i$$

Solving the system of congruences

(TC 31.5–2)

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$$x \equiv 1 \pmod{3}$$

$$x \equiv 4 \pmod{5}$$

$$x \equiv 2 \pmod{7}$$

$$x \equiv 9 \pmod{11}$$

Solving the system of congruences

CRT with non-pairwise coprime moduli

$$\begin{cases} x \equiv 3 \pmod{8} \\ x \equiv 11 \pmod{20} \\ x \equiv 1 \pmod{15} \end{cases}$$