01204211 Discrete Mathematics
Lecture 8a: Integers and GCD

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Number theory: integers and divisibility

In the third part of the course, we study number theory, a once-thought-to-be "useless" branch of mathematics.

Why?

- The topic itself is very very beautiful.
- It has many applications in cryptography and error correcting codes.

We will cover:

- Basic concepts of divisibility, prime numbers, and congruence.
- How to quickly check if a number is prime.
- How to essentially perform "division" with integers, allowing us to work with important and useful objects like polynomials using only integers.
- Applications like cryptography (RSA), secret sharing, erasure codes and error correcting codes.

Definitions

Definition (divisibility)

We say that an integer a **divides** b or b **is divisible by** a if there exist an integer k such that

$$b = ak.$$

If it is the case, we also write $a|b$. We also say that a is a **divisor** (or a **factor**) of b. On the other hand if a does not divide b, we write $a \not| b$.

Examples

If $a|b$ and $a|c$, prove that $a|(b+c)$.

If $a|b$ and $b|c$, prove that $a|c$.

Remainder

Defintion (remainder)

The **remainder** of the division of b with a is an integer r when there exists an integer q such that

$$b = qa + r,$$

where $0 \leq r < a$.
We refer to q as the **quotient** of the division.

Examples:

We use operator `mod` to denote an operation for finding the remainder of a division.
I.e., $a \bmod b$ is the remainder of dividing a with b.

Examples

Let r be the remainder of the division of b by a. Assume that $c|a$ and $c|b$. Prove that $c|r$.

More examples

For every integer a, $a - 1 | a^2 - 1$.

Primes

Definition (primes)

- An integer $p > 1$ is a **prime** if its divisors are only p, $-p$, 1, and -1.
- If an integer $n > 1$ is not a prime, it is called a **composite**.
- Note: 1 is not a prime and also not a composite.

Fundamental theorem of arithmetic

Unique factorization

Every integer greater than 1 can be represented uniquely as a product of prime numbers, up to the order of the factors.

Algorithm for testing primes

Recall our `CheckPrime2` algorithm

```
Algorithm CheckPrime2(n):  // Input: an integer n
    if n <= 1:
        return False
    let s = square root of n
    i = 2
    while i <= s:
        if n is divisible by i:
            return False
        i = i + 1
    return True
```

How fast can it run? Note that $s = \sqrt{n}$; therefore, it takes time $O(\sqrt{n})$ to run.

Efficient algorithms

Is $O(\sqrt{n})$ for checking a prime number efficient?
What is the "size" of the input to the problem? The input contains one integer n; is the size of the input just 1?
When working with input consisting only a few numbers, we typically use the number of bits. For integer n, the number of bits of n is $\lceil \log_2 n \rceil$.

n	number of bits of n	$\sqrt{n}$
2	1	1.414
4	2	2
16	4	4
1,024	10	32
1,048,576	20	1,024
1,125,899,906,842,624	50	33,554,432
1,267,650,600,228,229,401,496,703,205,376	100	1,125,899,906,842,624

Side note: Recall that the first step in RSA is to find a pair of large primes. Typically we want them to be of size in the *thousand* bits.

Greatest Common Divisors (GCD)

Definition (GCD)

For integers x and y, the **greatest common divisor** (or GCD) of x and y is the largest integer g such that $g|x$ and $g|y$. We refer to it as $gcd(x, y)$.

A simple way to find $gcd(x, y)$:

```
g = min(x,y)
while (x mod g != 0) or (y mod g != 0):
  g -= 1
return g
```

What is the running time of this algorithm? Does it run in polynomial time on the size of the input?

Euclid's algorithm

```
Algorithm Euclid(x,y):
  if x mod y == 0:
    return y
  else:
    return Euclid(y, x mod y)
```

Let's see how it works with $Euclid(12311, 24324)$:

Euclid(12311, 24324)
Euclid(24324, 12311)
Euclid(12311, 12013)
Euclid(12013, 298)
Euclid(298, 93)
Euclid(93, 19)
Euclid(19, 17)
Euclid(17, 2)
Euclid(2, 1)

Proofs

We have to prove two properties:

- For any integers x and y, $\mathrm{Euclid}(x, y) = gcd(x, y)$.
- The running time of Euclid.

Note that when $x < y$, $\mathrm{Euclid}(x, y)$ just calls itself with both arguments swapped, i.e., $\mathrm{Euclid}(y, x)$. After that, in each call, x is always larger than y. For simplicity of the analysis, we shall work only with the case that $x > y$.

Theorem 1

For any integers x and y such that $x > y$, $\mathrm{Euclid}(x, y) = gcd(x, y)$.

Proof.

We prove using strong induction. For the base case, note that when $y|x$, $gcd(x, y) = y$; therefore, the base case of the algorithm is correct.
Our induction hypothesis is: for any $x' < x$ and $y' < y$, $\mathrm{Euclid}(x', y') = gcd(x', y')$.
Now assume that $y \not| x$. The Euclid algorithm returns $\mathrm{Euclid}(y, x \bmod y)$ as the gcd. Note that $y < x$ and $x \bmod y < y$. Therefore, we can use the I.H. to claim that

$$\mathrm{Euclid}(y, x \bmod y) = gcd(y, x \bmod y).$$

Thus, we are left to show that

$$gcd(x, y) = gcd(y, x \bmod y).$$

□

What is $x \bmod y$?

Let $\lfloor a \rfloor$ be the largest integer a' such that $a' \leq \lfloor a \rfloor$.

$$x \bmod y = x - \left\lfloor \frac{x}{y} \right\rfloor \cdot y$$

Lemma 2

If $a|x$ *and* $a|y$*, then* $a|x \bmod y$*.*

Lemma 3

$gcd(x, y) = gcd(y, x \bmod y)$

How many recursive calls does Euclid's algorithm makes?

Consider Euclid(x, y):

- If we start with $x < y$, the next calls will always have that $x > y$; so we have at most one call with $x < y$.
- When can we decrease the value of x or y in the calls?
- When $y \leq x/2$, when Euclid(x, y) calls Euclid$(y, x \bmod y)$ the first argument decreases by half.
- How about when $y > x/2$?
  Euclid$(x, y) \Rightarrow$ Euclid$(y, x \bmod y) \Rightarrow$ Euclid$(x \bmod y, y \bmod (x \bmod y))$ Note that in this case, $x \bmod y = x - y \leq x/2$. Thus, after two recursive calls, the first argument decreases by half.
- How many times can that happen?
- The first argument can decrease by a factor of two for at most $\log x$ times. Therefore, the Euclid algorithm runs in time $O(\log \max\{x, y\}) = O(\log x + \log y)$.

Computing power

How fast can we compute x^y?

```
Algorithm power(x,y):
  a = 1
  for i = 1,2,...,y:
    a *= x
  return a
```

What is the running time? Is it efficient?

Repeated squaring

If y is a power of two, we can find x^y using small number of multiplications using repeated squaring. E.g.,

$$x^{16} = (x^8)^2 = ((x^4)^2)^2 = (((x^2)^2)^2)^2.$$

```
Algorithm power(x,y):  // for y=2^k
  if y == 0:
    return 1
  else:
    a = power(x, y / 2)
    return a*a
```

Repeated squaring (general y)

```
Algorithm power(x,y):
  if y == 0:
    return 1
  else:
    a = power(x, floor(y / 2))
    if y mod 2 == 0:
      return a*a
    else
      return a*a*x
```

What is the number of recursive calls?
What is the running time?
While the number of multiplication is small, the numbers involved is huge as x^y has $y \log x$ bits. Computing x^y exactly definitely takes a long time.

Repeated squaring (general y, mod n)

Computing $x^y \bmod n$:

```
Algorithm power(x,y,n):
  if y == 0:
    return 1
  else:
    a = power(x, floor(y / 2)) mod n
    if y mod 2 == 0:
      return a*a mod n
    else
      return a*a*x mod n
```