Factorization and Primality Testing Chapter 1 Background

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September 11, 2024

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- A substantial portion of this course is theoretical and solutions to problems will require the writing of proofs.
- Some other parts of the course will require the writing of computer programs using multiprecision arithmetic.
- In view if the close connections with security protocols this is a rapidly moving area, and one is never quite sure of the current state-of-the-art since many security organizations do not publish their work.

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- Another deficiency is that there is no proper discussion of relative run-times. This needs some understanding of analytic number theory, a topic which only covered fully in graduate classes. We will give an overview of the more elementary aspects.

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- Another deficiency is that there is no proper discussion of relative run-times. This needs some understanding of analytic number theory, a topic which only covered fully in graduate classes. We will give an overview of the more elementary aspects.
- A more advanced text which covers these topics is Crandall and Pomerance, Prime Numbers:A Computational Perspective, Springer, ISBN–10: 0387252827, ISBN–13: 978-0387252827

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  is a one-line proof of the factorization of 105.
- And $101 = d.q + r$ with

$$\begin{aligned} d &= 2, q = 50, r = 1 \\ d &= 3, q = 33, r = 2 \\ d &= 5, q = 20, r = 1 \\ d &= 7, q = 14, r = 3 \end{aligned}$$

  gives a proof that 101 is prime.

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- If you want to experiment I suggest using the package PARI which runs on most computer systems and is available at `https://pari.math.u-bordeaux.fr/`

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- Checking 2^{1000} might seem difficult but it is actually very easy.

$1000 = 2^3 + 2^5 + 2^6 + 2^7 + 2^8 + 2^9, 2^{1000} = 2^{2^3} 2^{2^5} 2^{2^6} 2^{2^7} 2^{2^8} 2^{2^9}$ and the 2^{2^k} can be computed by successive squaring, so

- $2^{2^3} = 256$, $2^{2^4} = 256^2 = 65536 \equiv 471$, $2^{2^5} \equiv 471^2 = 221841 \equiv 620$,

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- So any programming language which can do double precision can compute 2^{p-1} modulo p in linear time.

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- One is often asked why one needs formal proofs.
- They are necessary, and as a general principle understanding the proof usually reveals the underlying structure which is the reason why the theorem is true.
- There is an instructive example due to J. E. Littlewood in 1912.

Littlewood

- Let $\pi(x)$ denote the number of prime numbers not exceeding x. Gauss had suggested that

$$\int_0^x \frac{dt}{\log t}$$

should be a good approximation to $\pi(x)$

$$\pi(x) \sim \mathrm{li}(x).$$

For all values of x for which $\pi(x)$ has been calculated it has been found that

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- Here is a table of values which illustrates this for various values of x out to 10^{22}.

x	$\pi(x)$	$\mathrm{li}(x)$
10^4	1229	1245
10^5	9592	9628
10^6	78498	78626
10^7	664579	664917
10^8	5761455	5762208
10^9	50847534	50849233
10^{10}	455052511	455055613
10^{11}	4118054813	4118066399
10^{12}	37607912018	37607950279
10^{13}	346065536839	346065645809
10^{14}	3204941750802	3204942065690
10^{15}	29844570422669	29844571475286
10^{16}	279238341033925	279238344248555
10^{17}	2623557157654233	2623557165610820
10^{18}	24739954287740860	24739954309690413
10^{19}	234057667276344607	234057667376222382
10^{20}	2220819602560918840	2220819602783663483
10^{21}	21127269486018731928	21127269486616126182

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- No! Littlewood in 1914 showed that there are infinitely many values of x for which
$$\pi(x) > \mathrm{li}(x)!$$
- We now believe that the first sign change occurs when
$$x \approx 1.387162 \times 10^{316} \tag{1.1}$$
well beyond what can be calculated directly.

Introduction to Number Theory

- For many years it was only known that the first sign change in $\pi(x) - \mathrm{li}(x)$ occurs for *some* x satisfying

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- Let me turn back to that table, as it illustrates something else very interesting.

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The Riemann Hypothesis

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- There is a million dollar prize for a proof, or a disproof. And probably an automatic professorship at the most prestigious universities for anyone who wins it.
- By the way, one might wonder if there is something random in the distribution of the primes. This is how random phenomena are supposed to behave.

Introduction to Number Theory

- Number theory in its most basic form is the study of the set of *integers*

$$\mathbb{Z} = \{0, \pm 1, \pm 2, \ldots\}$$

and its important subset

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  the set of positive integers, sometimes called the *natural numbers*.
- The usual rules of arithmetic apply, and can be deduced from a set of axioms. If you multiply any two members of $\mathbb{Z}$ you get another one. Likewise for $\mathbb{N}$

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- But this last fails for $\mathbb{N}$.
- You can do other standard things in $\mathbb{Z}$, such as

$$x(y+z) = xy + xz$$

  and

$$xy = yx$$

  is always true.

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Example 1

If $a|b$ and $b|c$, then $a|c$.

- The proof is easy.

Proof.

There are d and e so that $b = ad$ and $c = be$. Hence $a(de) = (ad)e = be = c$ and de is an integer. □

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- For any a we have $0a = 0$.
- If $ab = 1$, then $a = \pm 1$ and $b = \pm 1$ (with the same sign in each case).
- Also if $a \neq 0$ and $ac = ad$, then $c = d$.

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Definition 2

A member of $\mathbb{N}$ greater than 1 which is only divisible by 1 and itself is called a prime number.

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- **Proof** One has to check for divisors d with $1 < d < 100$.
- Moreover if d is a divisor, then there is an e so that $de = 101$, and one of d, e is $\leq \sqrt{101}$ so we only need to check out to 10.

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- Moreover if d is a divisor, then there is an e so that $de = 101$, and one of d, e is $\leq \sqrt{101}$ so we only need to check out to 10.
- So we only need to check the primes $2, 3, 5, 7$. Moreover 2 and 5 are not divisors and 3 is easily checked, so only 7 needs any work, and this leaves remainder 3, not 0.

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- **Proof.** This uses induction.
- 1 is an "empty product" of primes, so case $n = 1$ holds.

- Since we are dealing with simple proofs for facts about $\mathbb{N}$ there is one proof method which is very important.
- This is the principle of induction. It is actually embedded into the definition of $\mathbb{N}$. That is, we have $1 \in \mathbb{N}$ and it is the least member and given any $n \in \mathbb{N}$ the next member is $n+1$. In this way one sees that $\mathbb{N}$ is *defined* inductively.
- A fundamental theorem.

Theorem 4

Every member of $\mathbb{N}$ is a product of prime numbers.

- **Proof.** This uses induction.
- 1 is an "empty product" of primes, so case $n = 1$ holds.
- Suppose that we have proved the result for all $m \le n$. If $n+1$ is prime we are done. Suppose $n+1$ is not prime. Then there is an a with $a|n+1$ and $1 < a < n+1$. Then also $1 < \frac{n+1}{a} < n+1$. But then on the inductive hypothesis both a and $\frac{n+1}{a}$ are products of primes.

- We can use this to deduce

Theorem 5 (*Euclid*)

There are infinitely many primes.

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$$m = p_1 p_2 \ldots p_n + 1.$$

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$$m = p_1 p_2 \ldots p_n + 1.$$

- Since we already know some primes it is clear that $m > 1$.
- Hence m is a product of primes, and in particular there is a prime p which divides m.
- But p is one of the primes $p_1, p_2, \ldots, p_n$ so $p | m - p_1 p_2 \ldots p_n = 1$. But 1 is not divisible by any prime. So our assumption must have been false.

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- It tells us more about the distribution of primes and is the beginning of the modern approach.
- Let

$$S(x) = \sum_{n\le x} \frac{1}{n}.$$

- Then

$$S(x) \ge \sum_{n\le x} \int_n^{n+1} \frac{dt}{t} \ge \int_1^x \frac{dt}{t} = \log x.$$

- Now consider

$$P(x) = \prod_{p\le x} (1 - 1/p)^{-1}$$

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- Note that when one multiplies out the left hand side every fraction $\frac{1}{n}$ with $n \le x$ occurs.

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- Note that when one multiplies out the left hand side every fraction $\frac{1}{n}$ with $n \le x$ occurs.
- Since $\log x \to \infty$ as $x \to \infty$, there have to be infinitely many primes.

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$$\sum_{p\leq x} \frac{1}{2} \sum_{k=2}^{\infty} \frac{1}{p^k} \leq \frac{1}{2}\sum_{n=2}^{\infty} \frac{1}{n(n-1)} = \frac{1}{2}.$$

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- Hence we have just proved that

$$\sum_{p\le x}\frac{1}{p} \ge \log\log x - \frac{1}{2}.$$

- Euler's result on primes is often quoted as follows.

Theorem 6 (Euler)

The sum

$$\sum_p \frac{1}{p}$$

diverges.

- We now come to something very important

Theorem 7 (The division algorithm)

Suppose that $a \in \mathbb{Z}$ and $d \in \mathbb{N}$. Then there are unique q, $r \in \mathbb{Z}$ such that $a = dq + r, \quad 0 \le r < d$.

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- **Proof.** Let $\mathcal{D} = \{a - dx : x \in \mathbb{Z}\}$.
- If $a \ge 0$, then $a \in \mathcal{D}$, and if $a < 0$, then $a - d(a-1) > 0$.

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- Moreover if $r \ge d$, then $a = d(q+1) + (r-d)$ gives another solution, but with $0 \le r - d < r$ contradicting the minimality of r.

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- Hence $r < d$ as required.
- For uniqueness note that a second solution $a = dq' + r'$, $0 \le r' < d$ gives $0 = a - a = (dq' + r') - (dq + r)$ $= d(q' - q) + (r' - r)$, and if $q' \ne q$, then $d \le d|q' - q| = |r' - r| < d$ which is impossible.

- It is exactly this which one uses when one performs long division

Example 8

Try dividing 17 into 192837465 by the method you were taught at primary school.

- We will make frequent use of the division algorithm, e.g.

Theorem 9

Given two integers a and b, not both 0, define

$$\mathcal{D}(a,b) = \{ax + by : x \in \mathbb{Z}, y \in \mathbb{Z}\}.$$

Then $\mathcal{D}(a,b)$ has positive elements. Let (a,b) denote the least positive element. Then (a,b) has the properties
(i) $(a,b)|a$,
(ii) $(a,b)|b$,
(iii) if the integer c satisfies $c|a$ and $c|b$, then $c|(a,b)$.

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- GCD

Definition 10

The number (a,b) is called the greatest common divisor of a and b. The symbol (a,b) has many uses in mathematics, so to be clear one sometimes writes $GCD(a,b)$.

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- Note that $GCD(a,b)$ divides every member of $\mathcal{D}(a,b)$.

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- Thus $r = a - (a, b)q = a - (ax + by)q$ for some integers x and y. Hence $r = a(1 - xq) + b(-yq)$.

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- Since $0 < r < (a,b)$ this contradicts the minimality of (a,b).
- Likewise for (ii).
- Now suppose $c|a$ and $c|b$, so that $a = cu$ and $b = cv$ for some integers u and v. Then

$$(a,b) = ax + by = cux + cvy = c(ux + vy)$$

so (iii) holds.

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Example 11

We have $\left(\frac{a}{(a,b)}, \frac{b}{(a,b)}\right) = 1$.

To see this observe that if $d = \left(\frac{a}{(a,b)}, \frac{b}{(a,b)}\right)$, then $d|\frac{a}{(a,b)}$ and $d|\frac{b}{(a,b)}$, and hence $d(a,b)|a$ and $d(a,b)|b$. But then $d(a,b)|(a,b)$ and so $d|1$, whence $d = 1$.

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Example 12

Suppose that a and b are not both 0. Then for any integer x we have $(a+bx, b) = (a, b)$. Here is a proof. First of all $(a,b)|a$ and $(a,b)|b$, so $(a,b)|a+bx$. Hence $(a,b)|(a+bx,b)$. On the other hand $(a+bx,b)|a+bx$ and $(a+bx,b)|b$ so that $(a+bx)|a+bx-bx=a$. Hence $(a+bx,b)|(a,b)|(a+bx,b)$ and so $(a,b) = (a+bx,b)$.

- Here is yet another

Example 13

Suppose that $(a, b) = 1$ and $ax = by$. Then there is a z such that $x = bz$, $y = az$. It suffices to show that $b|x$, for then the conclusion follows on taking $z = x/b$. To see this observe that there are u and v so that $au + bv = (a, b) = 1$. Hence $x = aux + bvx = byu + bvx = b(yu + vx)$ and so $b|x$.

- Following from the previous theorem we have a corollary.

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Suppose that a and b are integers not both 0. Then there are integers x and y such that

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- As a first application we establish

Theorem 15 (Euclid)

Suppose that p is a prime number, and a and b are integers such that $p|ab$. Then either $p|a$ or $p|b$.

- You might think this is obvious, but look at the following

Example 16

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$$5, 9, 13, 17, 21, 29, 33, 37, 41, 49 \ldots$$

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- Also the "prime" factorisation of 45 is 5×9.

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- Also the "prime" factorisation of 45 is 5×9.
- Now look at $441 = 9\times 49 = 21^2$.

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Example 16

Consider the set $\mathcal{A}$ of integers of the form $4k+1$.

- If you multiply two elements, e.g. $(4k_1+1)(4k_2+1) = 16k_1k_2+4k_2+4k_1+1 = 4(4k_1k_2+k_1+k_2)+1$ you get another of the same kind.
- We define a "prime" p in this system if it is only divisible by 1 and itself in the system.
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- Wait a minute, here factorisation is not unique!
- The theorem is false in $\mathcal{A}$ because $21|9\times 49$ but 21 does not divide 9 or 49!

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- Amazingly we have to use the additive structure to get something fundamental about the multiplicative structure.
- This is of huge significance and underpins some of the most fundamental questions in mathematics.

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- But then $b = abx + pby$ and since $p|ab$ we have $p|b$ as required.

- We can use Euclid's theorem to establish the following

Theorem 17

Suppose that $p, p_1, p_2, \ldots, p_r$ are prime numbers and

$$p | p_1 p_2 \ldots p_r.$$

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- If $p | p_1 p_2 \ldots p_r$, then by the inductive hypothesis we must have $p = p_j$ for some j with $1 \le j \le r$.

- We can now establish the main result of this section.

Theorem 18 (The Fundamental Theorem of Arithmetic)

Factorization into primes is unique apart from the order of the factors. More precisely if a is a non-zero integer and $a \neq \pm 1$, then

$$a = (\pm 1) p_1 p_2 \dots p_r$$

for some $r \geq 1$ and prime numbers $p_1, \dots, p_r$, and r and the choice of sign is unique and the primes p_j are unique apart from their ordering.

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- Note that we can even write

$$a = (\pm 1)p_1 p_2 \ldots p_r$$

when $a = \pm 1$ by interpreting the product over primes as an empty product in that case.

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- Now suppose that $r \geq 1$ and we have established uniqueness for all products of r primes, and we have a product of $r + 1$ primes, and

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- Then we see from the previous theorem that $p'_1 = p_j$ for some j and then

$$p'_2 \dots p'_s = p_1 p_2 \dots p_{r+1} / p_j$$

and we can apply the inductive hypothesis to obtain the desired conclusion.

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- Suppose a and b are positive integers. Then by the previous theorem we can write

$$a = p_1^{r_1} \dots p_k^{r_k}, \quad b = p_1^{s_1} \dots p_k^{s_k}$$

where the $p_1, \dots p_k$ are the different primes in the factorization of a and b and we allow the possibility that the exponents r_j and s_j may be zero.

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where the $p_1, \dots p_k$ are the different primes in the factorization of a and b and we allow the possibility that the exponents r_j and s_j may be zero.
- For example if $p_1 = 2$, $p_2 = 3$, $p_3 = 5$, then

$$20 = p_1^2 p_2^0 p_3^1,\ 75 = p_1^0 p_2^1 p_3^2,\ (20, 75) = 5 = p_1^0 p_2^0, p_3^1.$$

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- Then it can be checked easily that

$$(a, b) = p_1^{\min(r_1,s_1)} \dots p_k^{\min(r_k,s_k)}.$$

- We can now introduce the idea of least common multiple

Definition 19

We can also introduce here the *least common multiple* LCM

$$[a, b] = \frac{ab}{(a, b)}$$

and this could also be defined by

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- The $LCM[a, b]$ has the property that it is the smallest positive integer c so that $a|c$ and $b|c$.

- At this point it is useful to remind ourselves of some further terminology

Definition 20

A composite number is a number $n \in \mathbb{N}$ with $n > 1$ which is not prime. In particular a composite number n can be written

$$n = m_1 m_2$$

with $1 < m_1 < n$, and so $1 < m_2 < n$ also.

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- Even so, for large n this is hugely expensive in time.

- The number $\pi(x)$ of primes $p \le x$ is approximately

$$\pi(x) \sim \int_2^x \frac{d\alpha}{\log \alpha} \sim \frac{x}{\log x}$$

where log denotes the natural logarithm.

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- Still exponential in the bit size.
- Trial division is feasible for n out to about 40 bits on a modern PC. Much beyond that it becomes hopeless.

- One area where trial division, or sophisticated variants thereof, are useful is in the production of tables of primes, or counts of primes such as the value of $\pi(x)$.

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- This is how the table I showed you earlier with gives values of $\pi(x)$ for $x \leq 10^{27}$ was constructed.
- The simplest form of this is the 'Sieve of Eratosthenes'.

- Construct a $\lfloor\sqrt{N}\rfloor \times \lfloor\sqrt{N}\rfloor$ array. Here $N = 100$.

0	1	2	3	4	5	6	7	8	9
10	11	12	13	14	15	16	17	18	19
20	21	22	23	24	25	26	27	28	29
30	31	32	33	34	35	36	37	38	39
40	41	42	43	44	45	46	47	48	49
50	51	52	53	54	55	56	57	58	59
60	61	62	63	64	65	66	67	68	69
70	71	72	73	74	75	76	77	78	79
80	81	82	83	84	85	86	87	88	89
90	91	92	93	94	95	96	97	98	99

Forget about 0 and 1, and then for each successive element remaining remove the proper mutliples.

- Thus for 2 we remove $4, 6, 8, \ldots, 98$.

X	X	2	3	X	5	X	7	X	9
X	11	X	13	X	15	X	17	X	19
X	21	X	23	X	25	X	27	X	29
X	31	X	33	X	35	X	37	X	39
X	41	X	43	X	45	X	47	X	49
X	51	X	53	X	55	X	57	X	59
X	61	X	63	X	65	X	67	X	69
X	71	X	73	X	75	X	77	X	79
X	81	X	83	X	85	X	87	X	89
X	91	X	93	X	95	X	97	X	99

- Then for the next remaining element 3 remove $6, 9, \ldots, 99$.

X	X	2	3	X	5	X	7	X	X
X	11	X	13	X	X	X	17	X	19
X	X	X	23	X	25	X	X	X	29
X	31	X	X	X	35	X	37	X	X
X	41	X	43	X	X	X	47	X	49
X	X	X	53	X	55	X	X	X	59
X	61	X	X	X	65	X	67	X	X
X	71	X	73	X	X	X	77	X	79
X	X	X	83	X	85	X	X	X	89
X	91	X	X	X	95	X	97	X	X

- Likewise for 5 and 7.

X	X	2	3	X	5	X	7	X	X
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X	X	X	53	X	X	X	X	X	59
X	61	X	X	X	X	X	67	X	X
X	71	X	73	X	X	X	X	X	79
X	X	X	83	X	X	X	X	X	89
X	X	X	X	X	X	X	97	X	X

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X	61	X	X	X	X	X	67	X	X
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X	X	X	83	X	X	X	X	X	89
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- Likewise for 5 and 7.

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X	X	X	23	X	X	X	X	X	29
X	31	X	X	X	X	X	37	X	X
X	41	X	43	X	X	X	47	X	X
X	X	X	53	X	X	X	X	X	59
X	61	X	X	X	X	X	67	X	X
X	71	X	73	X	X	X	X	X	79
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- By counting the entries that remain one finds that $\pi(100) = 25$.

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- Of course if n is prime, then perforce $x-y=1$ and $x+y=2k+1$ so this would be the only solution.
- But if we could find a solution with $x-y>1$, then that would show that n is composite and would give a factorization.

- If $n = m_1 m_2$ with n odd and $m_1 \le m_2$, then m_1 and m_2 are both odd and there is a solution with

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- Another

Example 22

$$1001 = 2025 - 1024 = 45^2 - 32^2$$

$$x = 45,\ y = 32,\ m_1 = x - y = 13,\ m_2 = x + y = 77.$$

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- It is not very likely that $x - y$ or $x + y$ are factors of n, but if we could compute

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then we might find that g differs from 1 or n and so gives a factorization.
- Moreover there is a very fast way of computing greatest common divisors.

- To illustrate this consider

Example 23

Let $n = 10001$. Then

$$8n = 80008 = 80089 - 81 = 283^2 - 9^2 = 274 \times 292.$$

Now

$$GCD(292, 10001) = 73,\ 10001 = 73 \times 137$$

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- We also want to find fast ways of solving equations like

$$kn = x^2 - y^2$$

in the variables k, s, y.

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For real numbers α we define the **floor function** $\lfloor\alpha\rfloor$ to be the largest integer not exceeding α.
Occasionally it is also useful to define the **ceiling function** $\lceil\alpha\rceil$ as the smallest integer u such that $\alpha \le u$. The difference $\alpha - \lfloor\alpha\rfloor$ is often called **the fractional part** of α and is sometimes denoted by $\{\alpha\}$.

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- By the way of illustration.

Example 25

$\lfloor\pi\rfloor = 3$, $\lceil\pi\rceil = 4$, $\lfloor\sqrt{2}\rfloor = 1$, $\lfloor-\sqrt{2}\rfloor = -2$, $\lceil-\sqrt{2}\rceil = -1$.

- The floor function has some useful properties.

Theorem 26 (Properties of the floor function)

(i) For any $\alpha \in \mathbb{R}$ *we have* $0 \le \alpha - \lfloor \alpha \rfloor < 1$.
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- Then $\alpha + k - \lfloor \alpha \rfloor - k = \theta$ and since there is only one integer l with $0 \le \alpha + k - l < 1$, and this l is $\lfloor \alpha + k \rfloor$ we must have $\lfloor \alpha + k \rfloor = \lfloor \alpha \rfloor + k$.

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