Divisibility & Unique Factorisation

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Definition

$$d \mid n \iff d \neq 0 \text{ and } n = dk \text{ for some integer } k$$

Both n and d must be integers, and $d \neq 0$ — this side condition is part of the definition, not an afterthought. Equivalently, $d \mid n \iff \frac{n}{d} \in \mathbb{Z}$.

All of these say the same thing:

- d divides n
- d is a divisor of n
- d is a factor of n
- n is a multiple of d

$d \nmid n$ means d does not divide n. Note that $d \mid n$ is a **statement** (it has a truth value) — $2 \mid 6$ is true, $10 \nmid 5$ is true since $\frac{5}{10} \notin \mathbb{Z}$.

Proving and disproving divisibility statements

The pattern for a direct proof: unfold $d \mid n$ into $n = dk$, do algebra, then re-fold into the definition by exhibiting the integer witness.

$\forall a, b, c \in \mathbb{Z}$**, if** $c \mid a$ **then** $c \mid ab$**.**

> Let $a, b, c \in \mathbb{Z}$ and suppose $c \mid a$. Then $\exists k \in \mathbb{Z}$ such that $a = ck$. Multiplying both sides by b: $ab = ckb = c(kb)$. Since $k, b \in \mathbb{Z}$ we have $kb \in \mathbb{Z}$. Thus $c \mid ab$. $\square$

$\forall m \in \mathbb{Z}$**,** $6m(2m + 10m^2)$ **is divisible by 4.**

> Let $m \in \mathbb{Z}$. Then $6m(2m+10m^2) = 2(3m) \cdot 2(m+5m^2) = 4(3m(m+5m^2))$. Since $m \in \mathbb{Z}$, $3m(m + 5m^2) \in \mathbb{Z}$. Thus $4 \mid 6m(2m + 10m^2)$. $\square$

$\forall a, b, c \in \mathbb{Z}$**, if** $a \mid (b + c)$ **then** $a \mid b$ **or** $a \mid c$ — **false**. Counterexample $a = 3, b = 4, c = 2$: $a \mid (b + c)$ since $3 \mid 6$, but $3 \nmid 4$ and $3 \nmid 2$.

$\forall a, b, m \in \mathbb{Z}$**, if** $m \mid (a + b)$ **then** $m \mid (a - b)$ — **false**. A counterexample needs the hypothesis true and the conclusion false:

	$m \mid (a + b)$	$m \mid (a - b)$	conditional
$m = 5, a = 20, b = 10$	$5 \mid 30$ T	$5 \mid 10$ T	T
$m = 5, a = 21, b = 13$	$5 \mid 34$ F	$5 \mid 8$ F	T
$m = 5, a = 27, b = 7$	$5 \mid 34$ F	$5 \mid 20$ T	T
$m = 5, a = 19, b = -9$	$5 \mid 10$ T	$5 \mid 28$ F	**F**
$m = 5, a = 23, b = 12$	$5 \mid 35$ T	$5 \mid 11$ F	**F**
$m = 5, a = -10, b = -3$	$5 \mid -13$ F	$5 \mid -7$ F	T

Only the two rows with hypothesis T and conclusion F are counterexamples.

$\forall m, n, q \in \mathbb{Z}$**, if** $m \mid n$ **and** $n \mid q$ **then** $m^2 \mid nq$ — **true**.

> Let m, n, q be non-zero integers with $m \mid n$ and $n \mid q$. By definition there exist $a, b \in \mathbb{Z}$ with $n = ma$ and $q = nb$. Then
>
> $$nq = (ma)(nb) = ma \cdot (mab) = m^2(a^2b).$$
>
> Since $a^2b \in \mathbb{Z}$, we conclude $m^2 \mid nq$. $\square$

If k **is even and** m **is odd, then** $(k + 2)^2 - (m - 3)^2$ **is divisible by 4.**

Let $k = 2a$ and $m = 2b+1$ for some $a, b \in \mathbb{Z}$. Then $(k+2)^2 = (2a+2)^2 = 4(a+1)^2$ and $(m-3)^2 = (2b-2)^2 = 4(b-1)^2$, so

$$(k+2)^2 - (m-3)^2 = 4((a+1)^2 - (b-1)^2),$$

and $(a+1)^2 - (b-1)^2 \in \mathbb{Z}$. □

$\forall c, d, e \in \mathbb{Z}$**, if** $c \mid d$ **and** $c \nmid e$**, then** $c \nmid (d+e)$**.**

Proof by contradiction. Suppose there exist integers c, d, e with $c \mid d$, $c \nmid e$ and $c \mid (d+e)$. Then $d = cx$ for some $x \in \mathbb{Z}$, and $d + e = cy$ for some $y \in \mathbb{Z}$. Hence $cx + e = cy$, so $e = c(y-x)$ with $y - x \in \mathbb{Z}$ — so $c \mid e$, a contradiction. □

Every integer $n > 1$ is a product of primes

Proof by contradiction. Suppose the theorem is false. Then there exists an integer $n > 1$ that is not a product of primes. **Choose the smallest such** n — such a smallest one exists by the well-ordering principle. Choosing the smallest is what lets us assume every integer strictly between 1 and n *is* a product of primes.

Every integer $n > 1$ is either prime or composite (not both).

Case 1: n is prime. Then n is a product of primes (namely itself) — contradiction.

Case 2: n is composite. Then $n = rs$ for positive integers r, s with $r \neq 1$ and $s \neq 1$, which forces $1 < r < n$ and $1 < s < n$. Because n was chosen smallest, both r and s are products of primes, say $r = p_1 p_2 \cdots p_k$ and $s = q_1 q_2 \cdots q_\ell$. Therefore $n = rs = p_1 \cdots p_k q_1 \cdots q_\ell$ is a product of primes too.

Either way n is a product of primes, contradicting our choice of n. □

Unique Factorisation Theorem

Provided in the exam. This theorem and the Quotient-Remainder Theorem are both stated on the *MATH1061/MATH7861 Examination Formula Page*, so they can be cited rather than restated from memory — see also logical-equivalence-laws[1] for the rest of what that page carries.

Given any integer $n > 1$, the **standard factored form** of n is

$$n = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}$$

where $k \in \mathbb{Z}^+$, the p_i are primes, the e_i are positive integers, and $p_1 < p_2 < \cdots < p_k$.

[1] courses/math1061/logical-equivalence-laws.pdf

Both the primes and their exponents are unique — this is what makes the factored form a canonical fingerprint of an integer, and it's the engine behind divisor counting, gcd and lcm (see gcd-lcm-and-euclidean-algorithm[2]).

Counting divisors from the factorisation

Any positive divisor of $n = p_1^{e_1} \cdots p_k^{e_k}$ has the form $p_1^{a_1} \cdots p_k^{a_k}$ with $0 \le a_i \le e_i$, so there are

$$(e_1 + 1)(e_2 + 1) \cdots (e_k + 1)$$

positive divisors.

$6975 = 3^2 \cdot 5^2 \cdot 31$, found by trial division: $6975 = 3 \cdot 2325 = 3 \cdot 3 \cdot 775 = 3 \cdot 3 \cdot 5 \cdot 155 = 3^2 \cdot 5^2 \cdot 31$. A divisor has 0, 1 or 2 threes; 0, 1 or 2 fives; and 0 or 1 thirty-ones — so $3 \cdot 3 \cdot 2 = 18$ positive divisors.

$27720 = 2^3 \cdot 3^2 \cdot 5 \cdot 7 \cdot 11$.

$1400 = 2^3 \cdot 5^2 \cdot 7$, worked through:

- $1400 = 2(700) = 2 \cdot 2(350) = 2 \cdot 2(35)(10) = 2^2(5 \cdot 7)(2 \cdot 5) = 2^3 \cdot 5^2 \cdot 7^1$ — note the primes are written in increasing order.
- $1400^2 = (2^3 \cdot 5^2 \cdot 7)^2 = 2^6 \cdot 5^4 \cdot 7^2$ — raising to a power **multiplies** the exponents.
- $1400^3 = 1400 \cdot 1400^2 = 2^9 \cdot 5^6 \cdot 7^3$ — multiplying **adds** the exponents.
- Number of positive divisors of 1400: $(3 + 1)(2 + 1)(1 + 1) = 24$.
- Divisors of 1400 divisible by 8: all factors of the form $2^3 \cdot 5^* \cdot 7^*$, i.e. $8, 40, 200, 56, 280, 1400$.
- Smallest n with $1400n$ a perfect square: $1400n = t^2$ needs every exponent even. $t^2 = 2^3 \cdot 5^2 \cdot 7^1 \cdot n$, and splitting each power in half (bigger halves on the left) gives $t = 2^2 \cdot 5^1 \cdot 7^1$ against $2^1 \cdot 5^1 \cdot 7^0 \cdot n$, so $n = 2 \cdot 7 = 14$.

Primality testing

Lemma: for every integer $n > 1$, if no integer x in the range $1 < x \le \sqrt{n}$ divides n, then n is prime.

This is why trial division only has to go as far as $\sqrt{n}$ — for 6975, only up to $\sqrt{6975} = 83.51\ldots$

> *Proof by contraposition.* The contrapositive is: $\forall n \in \mathbb{Z}^{\ge 2}$, if n is not prime, then there exists an integer x with $1 < x \le \sqrt{n}$ such that $x \mid n$.
>
> Suppose $n \in \mathbb{Z}^{\ge 2}$ and n is not prime. Then n is composite, so by definition $\exists r, s \in \mathbb{Z}^+$ with $n = rs$ and $1 < r < n$ and $1 < s < n$.

[2] courses/math1061/gcd-lcm-and-euclidean-algorithm.pdf

Case 1: $r = s$. Then $r = s = \sqrt{n}$.

Case 2: $r \neq s$. Then one of r, s is less than $\sqrt{n}$ and the other greater — if both were greater we'd have $rs > n$, and if both were less we'd have $rs < n$.

In either case there is an $x \in \{r, s\}$ with $1 < x \leq \sqrt{n}$ and $x \mid n$. □

There are infinitely many primes

Lemma: for any integer a and any prime p, if $p \mid a$ then $p \nmid (a+1)$.

Proof by contradiction. Let $a \in \mathbb{Z}$, let p be prime, suppose $p \mid a$, and assume for a contradiction that $p \mid (a+1)$. Since $p \mid a$ there exists $k \in \mathbb{Z}$ with $a = pk$; since $p \mid (a+1)$ there exists $\ell \in \mathbb{Z}$ with $a + 1 = p\ell$. So

$$1 = (a+1) - a = p\ell - pk = p(\ell - k),$$

and $\ell - k \in \mathbb{Z}$, so $p \mid 1$. But $p \geq 2$ for any prime, whereas $p \mid 1$ forces $p = \pm 1$ — a contradiction. □

Theorem: there are an infinite number of primes.

Proof by contradiction. Suppose the number of primes is finite. Then some prime p is the largest, and we can list every prime in ascending order: $2, 3, 5, 7, 11, \ldots, p$.

Let $N = (2 \cdot 3 \cdot 5 \cdot 7 \cdot 11 \cdots p) + 1$.

Then $N > 1$, so by the Unique Factorisation Theorem N is a product of primes and hence divisible by some prime q. Because q is prime it must be one of $2, 3, 5, 7, 11, \ldots, p$.

So q divides $2 \cdot 3 \cdot 5 \cdots p$ — that is, $q \mid (N-1)$ — and hence by the lemma $q \nmid ((2 \cdot 3 \cdot 5 \cdots p) + 1) = N$.

So q divides N and q does not divide N: a contradiction. Therefore the original statement is true. □

See also

- proof-techniques[3] · modular-arithmetic[4] · gcd-lcm-and-euclidean-algorithm[5]
- practice-problems[6] — §13 Divisibility, with full worked solutions

[3] courses/math1061/proof-techniques.pdf
[4] courses/math1061/modular-arithmetic.pdf
[5] courses/math1061/gcd-lcm-and-euclidean-algorithm.pdf
[6] courses/math1061/practice-problems.pdf