Division Algorithm

Thm (Division Algorithm): Let $d \in \mathbb{N}$. Then for any $n \in \mathbb{Z}$, there exists a unique $q \in \mathbb{Z}$ and a unique $r \in \mathbb{Z}$ such that

$$n = dq + r$$

and $0 \le r \le d-1$.

$$(\forall d \in \mathbb{N})(\forall n \in \mathbb{Z})(\exists! q \in \mathbb{Z})(\exists! r \in \mathbb{Z})\left[(n = dq + r) \wedge (0 \le r \le n-1)\right]$$

Warm-Up: Let $d = 6$, $n = 317$. Find q and r.

Here,
q is the quotient
r is the remainder
n is the dividend (numerator)
d is the divisor (denominator)

Note: $\underset{\text{in } \mathbb{Z}}{n = dq + r} \iff \underset{\text{in } \mathbb{Q}}{\frac{n}{d} = q + \frac{r}{d}}$

Proof: Let $d \in \mathbb{N}$ and $n \in \mathbb{Z}$. We must prove two things:

Existence: There exist $q, r \in \mathbb{Z}$ satisfying the theorem statement.

Uniqueness: If q_1, r_1 and q_2, r_2 both satisfy the theorem, then $q_1 = q_2$ and $r_1 = r_2$.

Part 1: Existence Consider all possible solutions to

$$n = dx + y$$

where $x, y \in \mathbb{Z}$ and $y \geq 0$.

Let S be the set of all y-values in these solutions.

i.e., $$S = \{ y \in \mathbb{Z} \mid y \geq 0 \text{ and } (\exists x \in \mathbb{Z})(y = n - dx) \}$$

Ex: $d = 6$, $n = 317$

x	$317 - 6x$
$\vdots$	$\vdots$
48	29
49	23
50	17
51	11
52	5
53	-1
54	-7
$\vdots$	$\vdots$

So $S = \{5, 11, 17, 23, \ldots\}$

The remainder is the smallest element.

We now show that S is non-empty.

Case 1: $n \geq 0$. Then taking $x = 0$, we have

$$y = n - d(0) = n \geq 0$$

so $n \in S$.

Case 2: $n < 0$. Then taking $x = n$, we have

$$y = n - d(n) = n(1-d).$$

Since $d \in \mathbb{N}$, $1-d \leq 0$. So $n(1-d) \geq 0$, and hence $n(1-d) \in S$.

Therefore S is nonempty. By the Well-Ordering Property, S has a smallest element. Call it r.

[Why does this work? If $0 \in S$, then 0 is the smallest element. Otherwise, S is a subset of $\mathbb{N}$ and we can use Well-Ordering.]

Since $r \in S$, there exists $q \in \mathbb{Z}$ such that

$$n = dq + r.$$

The only thing left to show is that $0 \le r \le d-1$.

Because $r \in S$, we have $0 \le r$.

Suppose that $r > d-1$. Then $r \ge d$ (since $r \in \mathbb{Z}$), so $r-d \ge 0$.

But since

$$n - d(q+1) = (n-dq) - d = r - d,$$

this means that $r-d \in S$. But this contradicts the fact that r is the least element of S. So $a \le d-1$ must be true.

Part 2: Uniqueness Suppose now that $q_1, q_2, r_1, r_2 \in \mathbb{Z}$ are such that

$$n = dq_1 + r_1,$$
$$n = dq_2 + r_2,$$

and $0 \le r_1 \le d-1$, $0 \le r_2 \le d-1$.

Now,

$$dq_1 + r_1 = dq_2 + r_2,$$

so

$$r_1 - r_2 = dq_2 - dq_1 = d(q_2 - q_1).$$

Thus, $d \mid (r_1 - r_2)$. But $-(d-1) \le r_2 \le 0$, so

$$d\cdot(-1) < -(d-1) \le \underbrace{r_1 - r_2}_{d\cdot(q_2-q_1)} \le d-1 < d\cdot 1$$

So the only possibility is $r_1 - r_2 = 0$, i.e., $r_1 = r_2$.

Now, $r_1 - r_2 = 0 = d\cdot(q_2 - q_1)$. Since $d \neq 0$ $(d \in \mathbb{N})$, this forces $q_2 - q_1 = 0$, i.e. $q_1 = q_2$. ✓

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