Math 4580: Abstract Algebra I

Lecturer: **Professor Michael Lipnowski**

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We didn't have any lecture on the first day, but Dr. Lipnowski did post a module on `carmen` about the syllabus and the course. This semester we will be covering the first few chapters of the book *Abstract Algebra: Theory and Applications* by Thomas Judson.

Definition 1

Set: A collection of distinct objects, considered as an object in its own right.

Axioms: A collection of objects S with assumed structural rules is defined by axioms.

Statement: In logic or mathematics, an assertion that is either true or false.

Hypothesis and Conclusion: In the statement "If P, then Q", P is the hypothesis and Q is the conclusion.

Mathematical Proof: A logical argument that verifies the truth of a statement.

Proposition: A statement that can be proven true.

Theorem: A proposition of significant importance.

Lemma: A supporting proposition used to prove a theorem or another proposition.

Corollary: A proposition that follows directly from a theorem or proposition with minimal additional proof.

1 January 8, 2025

Professor Lipnowski discussed Sam Lloyd's 15 puzzle. Each lecture will include a mystery digit, contributing up to 5% bonus to the final grade based on correct guesses.

Certain course expectations:

- All assignments (one every two weeks) and exams (one midterm and one final exam) will be take-home.
- All the problems from the course textbook.
- Collaboration is encouraged, but the work should be your own.
- For the exams, we are not supposed to talk to other friends.

1.1 Functions

Definition 2

Let A and B be sets. A function $f : A \to B$ assigns exactly one output $f(a) \in B$ to every input $a \in A$.

- The set A is called the **domain** of f.
- The set B is called the **codomain** of f.

Fact 3

The domain A, codomain B, and the assignment of outputs $f(a)$ to every input $a \in A$ are all part of the data defining a function. Just writing a formula like $f(x) = e^x$ does not determine a function, as the domain and codomain are not specified.

For example:

- $f : \mathbb{R} \to \mathbb{R}$, $f(x) = e^x$.
- $f : \mathbb{Q} \to \mathbb{Q}$, $f(x) = e^x$.

Although these functions use the same formula, their meanings are completely different because their domains and codomains differ.

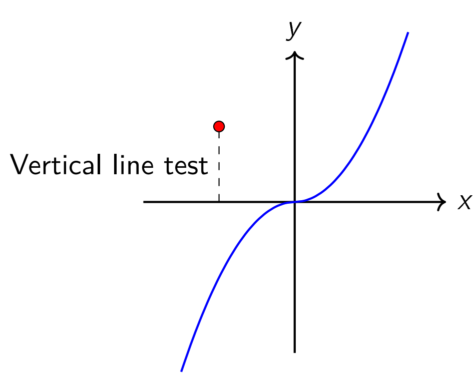
1.2 Graphs

A function $f : A \to B$ is often identified with its **graph** in $A \times B$:

$$\operatorname{graph}(f) = \{(a, b) \in A \times B : b = f(a)\}.$$

Lemma 4

Let $f : A \to B$ be a function. Its graph, $\operatorname{graph}(f)$, passes the **vertical line test**: For every $a \in A$, $V_a := \{(a, b) \in A \times B : b \in B\}$ intersects $\operatorname{graph}(f)$ in exactly one element.



Proposition 5

Let $G \subseteq A \times B$ be any subset passing the vertical line test, i.e., for all $a \in A$, $V_a \cap G$ consists of exactly one element. Then $G = \operatorname{graph}(f)$ for a unique function $f : A \to B$.

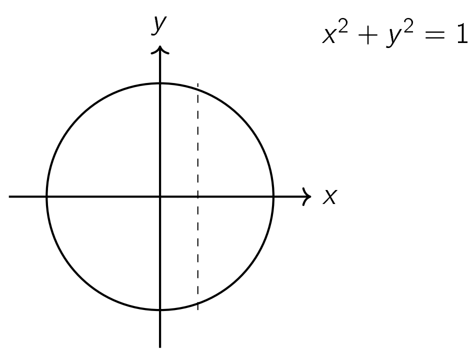
Proof. If $G = \{(a, b) \mid b \in B\}$ satisfies the vertical line test, define $f : A \to B$ by $f(a) = b$. Then $G = \text{graph}(f)$. $\square$

Definition 6

A subset $R \subseteq A \times B$ is called a **relation**. The vertical line test distinguishes graphs of functions from more general relations.

1.3 Examples

- Let $S = \{(x, y) \in \mathbb{R}^2 : x^2 + y^2 = 1\}$ (the unit circle). This is a relation but not the graph of a function because it fails the vertical line test: The vertical line $x = 0$ intersects the circle at two points.
- Visual depiction of a unit circle:



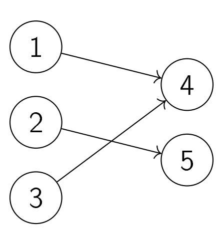
- Let $A = \{1, 2, 3\}$, $B = \{4, 5\}$. The number of functions from A to B is $2^3 = 8$, corresponding to the 8 associated graphs in $A \times B$.
- The number of relations from A to B is $2^{|a| \cdot |b|} = 2^{3 \cdot 2} = 64$, containing the 8 graphs of functions from A to B.

Fact 7

The notion of relation is much more permissive than the notion of functions.

1.4 Visualizing Functions as Directed Edges

A function $f : A \to B$ can be visualized as a collection of directed edges $(a, f(a)) \in A \times B$. Each element of A has exactly one outgoing edge in the graph.



2 January 10, 2025

2.1 Injection and Surjection

Let $f : A \to B$ be a function.

Definition 8 (Injectivity (One-to-One))
f is injective (one-to-one) if:

$$\forall x, y \in A,\ f(x) = f(y) \implies x = y$$

Equivalently:

$$x \neq y \implies f(x) \neq f(y)$$

Fact 9
Distinct inputs have distinct outputs.

Definition 10 (Surjectivity (Onto))
f is surjective (onto) if:

$$\forall b \in B,\ \exists a \in A \text{ such that } f(a) = b.$$

Fact 11
Every $b \in B$ is an output of something through f."

Example 12

Here are a few examples of injectivity and surjectivity:

- Let $A = \{1, 2, 3\}$ and $B = \{4, 5\}$ and $f : A \to B$ with $f(1), f(2), f(3)$ as elements of B. If B has only two elements, at least two of $f(1), f(2), f(3)$ must coincide (e.g., $f(1) = f(2)$). Thus, f is not injective.
- Let $A = \{1, 2, 3\}$ and $B = \{4, 5, 6, 7\}$ and $f : A \to B$ where:
$$f(1) = 4,\ f(2) = 7,\ f(3) = 5.$$
Distinct inputs have distinct outputs, so f is injective.
- Let $A = \{1, 2, 3\}$ and $B = \{4, 5, 6, 7\}$ and $f : A \to B$ where:
$$f(1) = 4,\ f(2) = 4,\ f(3) = 6.$$
Here, $A = \{1, 2, 3\}$ and $B = \{4, 5, 6, 7\}$ and $f(1) = f(2)$ but $1 \neq 2$, so f is not injective.
- Let $f : A \to B$ where B has size 4 and $f(1), f(2), f(3)$ are distinct elements of B. If $B \setminus \{f(1), f(2), f(3)\}$ is non-empty, then $b \neq f(a)$ for all $a \in A$, implying f is non surjective.
- Let $A = \{1, 2, 3\}$ and $B = \{4, 5\}$ and $f : A \to B$ with $f(1) = 4, f(2) = 5, f(3) = 4$. f is surjective.
- Let $A = \{1, 2, 3\}$ and $B = \{4, 5\}$ and $f : A \to B$ with $f(1) = 4, f(2) = 4, f(3) = 4$. f is not surjective.

2.2 Bijection and Range

Definition 13 (Bijectivity)

f is bijective if f is both injective and surjective.

Definition 14

Let $f : A \to B$ be a function. The *range* of f is the subset of B defined as:

$$\text{range}(f) := \{b \in B \mid b = f(a) \text{ for some } a \in A\}.$$

Thus, $f : A \to B$ is surjective $\iff \text{range}(f) = B$.

- Let $A = \{1, 2, 3\}$ and $B = \{4, 5, 6\}$ and $f : A \to B$ where:
$$f(1) = 6,\ f(2) = 5,\ f(3) = 4.$$
f is a bijection.

- Let $A = \{1, 2, 3\}$ and $B = \{4, 5, 6, 7\}$ and $f : A \to B$ where:

$$f(1) = 4,\ f(2) = 4,\ f(3) = 56$$

  f is neither injective nor surjective.

Question. *Let A and B be finite sets of the same size. Prove that the following are equivalent:*

1. *$f : A \to B$ is injective.*
2. *$f : A \to B$ is bijective.*
3. *$f : A \to B$ is surjective.*

Demonstrate that (1), (2), and (3) are not necessarily equivalent if $A = B = \mathbb{N}$.

Example 15

Let $f : \mathbb{N} \to \mathbb{Z}$ be defined as:

$$f(n) = \begin{cases} n/2 & \text{if } n \text{ is even,} \\ -\frac{(n+1)}{2} & \text{if } n \text{ is odd.} \end{cases}$$

is a bijection from $\mathbb{N}$ to $\mathbb{Z}$.

Proof. We will prove injectivity first. Suppose $f(n_1) = f(n_2)$. Then: If $f(n_1) = f(n_2) > 0$, then n_1 and n_2 must be even, and

$$\frac{n_1}{2} = f(n_1) = f(n_2) = \frac{n_2}{2} \implies n_1 = n_2.$$

If $f(n_1) = f(n_2) < 0$, then n_1 and n_2 must be odd, and

$$-\frac{n_1+1}{2} = f(n_1) = f(n_2) = -\frac{n_2+1}{2} \implies n_1 = n_2.$$

In all cases, $n_1 = n_2$. It follows that f is injective.

Now let's prove surjectivity. Let $n \in \mathbb{Z}$. If $n > 0$, then

$$n = f(2n).$$

If $n < 0$, then

$$n = f(-2n-1).$$

Therefore, f is surjective. □

Theorem 16 (Taylor's Theorem)

Let f be a function that is n-times differentiable at a. Then for each x in the interval containing a, there exists a ξ between a and x such that

$$f(x) = f(a) + f'(a)(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \cdots + \frac{f^{(n)}(a)}{n!}(x-a)^n + \frac{f^{(n+1)}(\xi)}{(n+1)!}(x-a)^{n+1}.$$

Proof. By the mean value theorem, for each x in the interval containing a, there exists a ξ between a and x such that

$$f(x) = f(a) + f'(a)(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \cdots + \frac{f^{(n)}(a)}{n!}(x-a)^n + R_{n+1}(x),$$

where $R_{n+1}(x)$ is the remainder term. The remainder term can be expressed as

$$R_{n+1}(x) = \frac{f^{(n+1)}(\xi)}{(n+1)!}(x-a)^{n+1}.$$

Therefore, we have

$$f(x) = f(a) + f'(a)(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \cdots + \frac{f^{(n)}(a)}{n!}(x-a)^n + \frac{f^{(n+1)}(\xi)}{(n+1)!}(x-a)^{n+1}.$$

□

3 January 13, 2025

Let n: Let $f : A \to B$, $g : B \to C$ be functions.

Their composition $g \circ f$ is defined as:

$$(g \circ f)(a) := g(f(a)) \text{ for all } a \in A.$$

3.1 Picture:

$$A \xrightarrow{f} B \xrightarrow{g} C$$

$$\xrightarrow{g \circ f}$$

3.2 Examples of Composition

1. $f : \mathbb{R} \to \mathbb{R}^3$, $g : \mathbb{R} \to \mathbb{R}^C$

$$x \mapsto x^3, \quad x \mapsto e^x.$$

$$\begin{aligned} g \circ f : A &\longrightarrow C \\ (g \circ f)(n) &:= g(f(n)) \\ &= g(x^3) \\ &= e^{x^3} \end{aligned}$$

3.3 Example 2

$$f : A \to B$$

$$1 \mapsto 6, \quad 2 \mapsto 4, \quad 3 \mapsto 4$$

$$g : B \to C$$

$$4 \mapsto 9, \quad 5 \mapsto 8, \quad 6 \mapsto 7$$

In Families

$$g \circ f : A \to C$$

$$(g \circ f)(1) := g(f(1)) = g(6) = 7$$

$$(g \circ f)(2) := g(f(2)) = g(4) = 9$$

$$(g \circ f)(3) := g(f(3)) = g(4) = 9$$

3.4 In Pictures: "Follow the Arrow!"

Associativity of Function Composition

Let $f : A \to B$, $g : B \to C$, $h : C \to D$ be functions. Then:

$$h \circ (g \circ f) = (h \circ g) \circ f.$$

For all $a \in A$:

$$\text{LHS}(a) = (h \circ (g \circ f))(a) = h(g(f(a)))$$

$$\text{RHS}(a) = ((h \circ g) \circ f)(a) = h(g(f(a)))$$

Proposition

Let $f : A \to B$ be a function. f is a bijection (i.e., f is 1-1 and onto) if and only if there exists a function $g : B \to A$ satisfying:

$$g \circ f = \text{id}_A$$

$$f \circ g = \text{id}_B$$

3.5 Rule:

The function g is said to be the inverse of f (and f is the inverse of g).

If g exists, it must be unique:

Suppose $h : B \to A$ also satisfies:

$$h \circ f = \mathrm{id}_A$$

$$f \circ h = \mathrm{id}_B$$

Then $g = h$.

Proof of Proposition

(b) Suppose $f : A \to B$ is 1-1 and onto.

Claim: For every $b \in B$, there is a unique element $g_b \in A$ for which $f(g_b) = b$.

Proof: Since f is onto, there is some g_b for which $f(g_b) = b$. If α also satisfies $f(\alpha) = b$, then:

$$f(\alpha) = b = f(g_b) \Rightarrow \alpha = g_b, \text{ since } f \text{ is 1-1.}$$

Thus, g_b exists and is unique.

Define $g : B \to A$ by:

$$b \mapsto g_b.$$

For all $b \in B$:

$$(f \circ g)(b) := f(g(b)) = f(g_b) = b \quad \text{by construction of } g_b.$$

$$\therefore f \circ g = \mathrm{id}_B.$$

For all $a \in A$:

$$(g \circ f)(a) := g(f(a)) = g_{f(a)}.$$

By construction of g:

$$f(g_{f(a)}) = f(a).$$

On the other hand:

$$f(a) = f(a).$$

Since f is 1-1, it follows that:

$$g_{f(a)} = a.$$

Thus:

$$(g \circ f)(a) = a \text{ for all } a \in A,$$

i.e., $g \circ f = \mathrm{id}_A$.

It follows that g, as constructed above, is the inverse of f.

Injective and Surjective

Suppose $f(x) = f(y)$ for some $x, y \in A$.

$$\Rightarrow g(f(x)) = g(f(y))$$

$$\Rightarrow (g \circ f)(x) = (g \circ f)(y)$$

$$\Rightarrow \mathrm{id}_A(x) = \mathrm{id}_A(y)$$

$$\Rightarrow x = y.$$

Thus, f is injective.

3.6 Surjective

Let $b \in B$.

$$\mathrm{id}_B = f \circ g$$

$$\text{Evaluate at } b:$$

$$b = (f \circ g)(b) = f(g(b))$$

Thus, $b = f(\text{something in } A)$.
Since b is arbitrary, f is surjective.

Equivalence Relation

Definition: An equivalence relation $\sim$ on the set X is a relation $\sim \subseteq X \times X$ satisfying:

$$\text{We write } x \sim y \text{ instead of } (x, y) \in \sim.$$

- (Reflexivity) $x \sim x$ for all $x \in X$.
- (Symmetry) $x \sim y$ if and only if $y \sim x$ for all $x, y \in X$.
- (Transitivity) $x \sim y$ and $y \sim z$ implies $x \sim z$ for all $x, y, z \in X$.

3.7 Example 1

Let $X = \mathbb{R}$.
Define $x \sim y$ by: $x - y = 2\pi k$ for some $k \in \mathbb{Z}$.

- (Reflexivity) For all $x \in \mathbb{R}$:

$$x - x = 0 = 2\pi \cdot 0 \in \mathbb{Z}.$$

  Thus, $x \sim x$.

- (Symmetry) $x \sim y \Rightarrow x - y = 2\pi k$ for some $k \in \mathbb{Z}$.

$$\Rightarrow y - x = 2\pi(-k) \in \mathbb{Z}.$$

  Thus, $y \sim x$.

- (Transitivity) $x \sim y$ and $y \sim z \Rightarrow x - y = 2\pi m$ and $y - z = 2\pi n$ for some $m, n \in \mathbb{Z}$.

$$\Rightarrow (x - y) + (y - z) = 2\pi(m + n) \in \mathbb{Z}.$$

  Thus, $x \sim z$.

3.8 Example 2

Let E be the union of 3 disconnected disks in $\mathbb{R}^2$.

Let $X = E$.

Define $x \sim y$ if there is a continuous path from x to y entirely within E.

- (Reflexivity) For all $x \in E$, the constant path $p(t) = x$ for all $t \in [0, 1]$ is continuous and satisfies $p(0) = p(1) = x$. Thus, $x \sim x$.

- (Symmetry) Suppose $x \sim y$. Then there is a continuous path $p : [0, 1] \to E$ with $p(0) = x$ and $p(1) = y$. Define $\overline{p}(t) = p(1 - t)$. Then $\overline{p}$ is continuous and satisfies $\overline{p}(0) = y$ and $\overline{p}(1) = x$. Thus, $y \sim x$.

- (Transitivity) Let $x \sim y$ and $y \sim z$. Then there are continuous paths $p : [0, 1] \to E$ with $p(0) = x$ and $p(1) = y$, and $q : [0, 1] \to E$ with $q(0) = y$ and $q(1) = z$. Define $r : [0, 1] \to E$ by:

$$r(t) = \begin{cases} p(2t) & 0 \leq t \leq \frac{1}{2} \\ q(2t - 1) & \frac{1}{2} \leq t \leq 1 \end{cases}$$

  Then r is a continuous path in E with $r(0) = x$ and $r(1) = z$. Thus, $x \sim z$.

4 January 15, 2025

4.1 Equivalence Relations and Equivalence Classes

Definition 17

Let $\sim$ be an equivalence relation on a set X. Let $x \in X$. The equivalence class of x is

$$[x] := \{y \in X : y \sim x\} \subset X$$

An equivalence class in X is a subset of X of the form $[x]$ for some $x \in X$.

Fact 18

The equivalence classes of X partition X into disjoint subsets. This partition completely encapsulates the equivalence relation.

Proposition 19

Let $a, b \in X$. Either:

- $[a]$ and $[b]$ are disjoint
- $[a] = [b]$

Proof. Suppose $[a]$ and $[b]$ are not disjoint. Let $t \in [a] \cap [b]$. Then $t \sim a$ and $t \sim b$.

$$\Rightarrow a \sim t \text{ and } t \sim b \quad \text{(by symmetry)}$$

$$\Rightarrow a \sim b \quad \text{(by transitivity)}$$

This implies that $[a] = [b]$:

$$\text{If } y \sim a, \text{ by } (a \sim b) \text{ and transitivity, } y \sim b \text{ too.}$$
$$\text{If } y \sim b, \text{ by } (b \sim a) \text{ and symmetry, } y \sim a.$$

It follows that

$$[a] = \{y \in X : y \sim a\} = \{y \in X : y \sim b\} = [b]$$

The latter proposition shows that equivalence classes on X partition X:

$$X = \bigsqcup_{i \in I} A_i$$

□

Definition 20

Let $X = \bigsqcup_{i \in I} A_i$ be the partition of X into equivalence classes for $\sim$. We call any subset $S \subset X$ a complete set of equivalence class representatives if it contains exactly one element $x_i \in A_i$ for every $i \in I$, i.e., "exactly one element per equivalence class".

In practice, understanding an equivalence relation amounts to understanding its associated equivalence classes and complete sets of equivalence class representatives.

4.2 Examples of Equivalence Classes

1. Let $X = \mathbb{R}$ and define the equivalence relation $\sim$ by $x \sim y$ if and only if $x - y \in 2\pi \cdot \mathbb{Z}$.

   The equivalence class of x is:
   $$[x] = \{x + 2\pi k : k \in \mathbb{Z}\} \subset \mathbb{R}$$

   Every $z \in \mathbb{R}$ lies in an equivalence class, namely $[z]$. If $[x]$ and $[y]$ contain a common element t, then there exist $k, l \in \mathbb{Z}$ such that:
   $$x + 2\pi k = t = y + 2\pi l \implies x - y = 2\pi(l - k) \implies x \sim y$$

   This implies $[x] = [y]$. Therefore, we have:
   $$\mathbb{R} = \bigsqcup_{[z]} [z]$$

   The interval $[0, 2\pi)$ is a complete set of equivalence class representatives.

2. Let X be the set of all 2×2 matrices, and define the equivalence relation $\sim$ by $x \sim y$ if there exists a continuous path $p : [0, 1] \to X$ with $p(0) = x$ and $p(1) = y$.

   The equivalence classes are the connected components of X. For example, if X consists of three disjoint disks $\mathbb{D}_1, \mathbb{D}_2, \mathbb{D}_3$, then:
   $$X = \mathbb{D}_1 \sqcup \mathbb{D}_2 \sqcup \mathbb{D}_3$$

   A complete set of equivalence class representatives is $\{\pi_1, \pi_2, \pi_3\}$, where $\pi_i \in \mathbb{D}_i$ for $i = 1, 2, 3$.

3. Let $X = \mathbb{R}^2$ and define the equivalence relation $\sim$ by $(a, b) \sim (c, d)$ if and only if $a^2 + b^2 = c^2 + d^2$.

   The equivalence class of (a, b) is the set of all points in $\mathbb{R}^2$ that lie on the circle centered at the origin with radius $\sqrt{a^2 + b^2}$.

Problem 21

Verify that the above defines an equivalence relation.

Equivalence classes:

$$[(a, b)] = \{(x, y) \in \mathbb{R}^2 : x^2 + y^2 = a^2 + b^2\}$$

$$\{(x, y) \in \mathbb{R}^2 : x^2 + y^2 = a^2 + b^2\}$$

is the collection of points in $\mathbb{R}^2$ having the same distance from $(0, 0)$ as (a, b), i.e., it is the circle in $\mathbb{R}^2$ centered at $(0, 0)$ passing through (a, b).

Equivalence classes for $\sim$ on $\mathbb{R}^2$: circles centered at $(0,0)$.

$$\mathbb{R}^2 = \bigsqcup_{a \in \mathbb{R}_{\geq 0}} [(a,0)]$$

and $\{(a,0) : a \in \mathbb{R}_{>0}\}$ is a complete set of equivalence class representatives.

5 January 17, 2025

5.1 Mathematical Induction

Definition 22

Let $\{P(n)\}_{n \in \mathbb{N}}$ be statements indexed by $n \in \mathbb{N} = \{0, 1, 2, \ldots\}$. Suppose

(a) $P(0)$ is true

(b) $P(m)$ true $\Rightarrow P(m+1)$ true for all $m \in \mathbb{N}$.

Then $P(n)$ is true for all $n \in \mathbb{N}$.

Fact 23

The following are true for a mathematical induction:

- (a) is the base case of the induction
- (b) is the inductive step
- Assuming $P(m)$ is true (in order to prove that $P(m+1)$ is true) is the inductive hypothesis.

5.1.1 Visualizing Induction

Picture the statements $P(0), P(1), P(2), \ldots$ as dominoes $0, 1, 2, \ldots$ lined up in some way. Our goal is to prove that all $P(n), n \in \mathbb{N}$ are true, amounting to toppling over every domino.

0 →	1 →	2 →	3 →	4 →	5
0+1	1+1	2+1	3+1	4+1	5+1

Base case $\Leftrightarrow$ we push over domino 0.

Inductive step $\Leftrightarrow$ if domino m topples, then domino $m+1$ topples too.

Inductive hypothesis $\Leftrightarrow$

Remark 24. *The inductive step is usually the hardest part of an inductive argument. However, as the above analogy shows, the base case is essential too: if no domino is pushed over, none will topple!*

5.2 Examples

1. Prove that

$$1 + 2 + \cdots + n = \frac{n(n+1)}{2}$$

Proof. Let $P(n) := 1 + \cdots + n = \frac{n(n+1)}{2}$.

Base case: When $n = 0$, the LHS $= 0$ (since the sum is empty) and the RHS $= 0$ too. So $P(0)$ is true.

Inductive Step: Suppose $P(m)$ is true, i.e.,

$$1 + \cdots + m = \frac{m(m+1)}{2}$$

Then

$$\begin{aligned} 1 + \cdots + m + (m+1) &= (1 + \cdots + m) + (m+1) \\ &= \frac{m(m+1)}{2} + (m+1) \quad \text{(by our inductive hypothesis)} \\ &= (m+1)\left(\frac{m}{2} + 1\right) \\ &= (m+1)\left(\frac{m+2}{2}\right) \\ &= \frac{(m+1)(m+2)}{2} \end{aligned}$$

So $P(m+1)$ is true too.

It follows, by induction, that $P(n)$ is true for all $n \in \mathbb{N}$, i.e.,

$$1 + 2 + \cdots + n = \frac{n(n+1)}{2}$$

□

2. Let $f_n = n^{\text{th}}$ Fibonacci number, defined as the n^{th} term of the sequence defined recursively by:

$$\begin{cases} f_0 = 0 \\ f_1 = 1 \\ f_n = f_{n-1} + f_{n-2} \text{ if } n \geq 2 \end{cases}$$

n	0	1	2	3	4	5	6	7	8
f_n	0	1	1	2	3	5	8	13	21

Now that

$$f_n = \frac{1}{\sqrt{5}}\left[\left(\frac{1+\sqrt{5}}{2}\right)^n - \left(\frac{1-\sqrt{5}}{2}\right)^n\right]$$

Note: $T_\pm := \frac{1\pm\sqrt{5}}{2}$ are the two roots of the quadratic equation $x^2 = x + 1$. T_+ is known as the golden ratio.

Proof. Let $P(n)$ denote the statement

$$f_n = \frac{1}{\sqrt{5}}\left(T_+^n - T_-^n\right)$$

We prove that $P(n)$ is true for all $n \in \mathbb{N}$ by induction:

Base case: $n = 0$:

$$\begin{aligned} f_0 = 0 &= \frac{1}{\sqrt{5}}\left(T_+^0 - T_-^0\right) \\ f_1 = 1 &= \frac{1}{\sqrt{5}}\left(\left(\frac{1+\sqrt{5}}{2}\right)^1 - \left(\frac{1-\sqrt{5}}{2}\right)^1\right) \\ &= \frac{1}{\sqrt{5}}\left(T_+^1 - T_-^1\right) \end{aligned}$$

Inductive step: Suppose $P(k)$ is true for all $k < m$. We will prove that $P(m)$ is true too:

If $m = 0$ or $m = 1$, we verified that $P(m)$ is true in our base case. Suppose $m \geq 2$.

$$\begin{aligned} f_m &= f_{m-1} + f_{m-2} \quad \text{(defining recursion for } f_m\text{)} \\ &= \frac{1}{\sqrt{5}}\left(T_+^{m-1} - T_-^{m-1}\right) \quad \text{(since } P(m-1) \text{ is true, by hypothesis)} \\ &+ \frac{1}{\sqrt{5}}\left(T_+^{m-2} - T_-^{m-2}\right) \quad \text{(since } P(m-2) \text{ is true, by hypothesis)} \\ &= \frac{1}{\sqrt{5}}\left(T_+^{m-1} + T_+^{m-2}\right) - \frac{1}{\sqrt{5}}\left(T_-^{m-1} + T_-^{m-2}\right) \\ &= \frac{1}{\sqrt{5}}\left(T_+^{m-2}(T_+ + 1)\right) - \frac{1}{\sqrt{5}}\left(T_-^{m-2}(T_- + 1)\right) \\ &= \frac{1}{\sqrt{5}}\left(T_+^{m-2} \cdot T_+^2\right) - \frac{1}{\sqrt{5}}\left(T_-^{m-2} \cdot T_-^2\right) \\ &= \frac{1}{\sqrt{5}}\left(T_+^m - T_-^m\right) \end{aligned}$$

Thus, $P(m)$ is true too. It follows that $P(n)$ is true for all $n \in \mathbb{N}$, i.e.,

$$f_n = \frac{1}{\sqrt{5}}\left(T_+^n - T_-^n\right) \text{ for all } n \in \mathbb{N}$$

□

The above proof uses the strong form of mathematical induction.

Theorem 25 (Principle of Mathematical Induction (strong form))
Let $\{P(n)\}_{n\in\mathbb{N}}$ be statements indexed by $n \in \mathbb{N} = \{0, 1, 2, \ldots\}$. Suppose

- (a) $P(0)$ is true
- (b) $P(0), P(1), \ldots, P(m) \Rightarrow P(m+1)$ true for all $m \in \mathbb{N}$.

Then $P(n)$ is true for all $n \in \mathbb{N}$.

Proof. Let $Q(n)$ be the statement that

$$P(0), P(1), \ldots, P(n) \text{ are all true.}$$

$Q(0)$ is true $P(0)$ is true. Suppose $Q(m)$ is true, i.e.,

$$P(0), \ldots, P(m) \text{ are all true.}$$

By (b) (the strong inductive step), $P(m+1)$ is true.

Thus, $P(0), \ldots, P(m), P(m+1)$ are all true by (b). It follows that $Q(m+1)$ is true too. By induction, $Q(n)$ is true for all $n \in \mathbb{N}$, implying that $P(n)$ is true for all $n \in \mathbb{N}$. □

6 January 22, 2025

6.1 Well-Ordering Principle

Theorem 26 (Well-ordering principle)
Let $S \subset \mathbb{N}$ be non-empty. Then S contains a least element t, i.e.,

- $t \in S$
- $t \leq s$ for all $s \in S$

Proof. Let $t \in S$. Consider the subset $S' = \{s \in S : s \leq t\} = S \cap \{0, \ldots, t\}$. Since S' is a non-empty subset of $\{0, \ldots, t\}$, it is finite. Therefore, S' has a least element, say t'. By construction, $t' \in S'$ and $t' \leq s$ for all $s \in S'$. Since $S' \subset S$, it follows that $t' \in S$ and $t' \leq s$ for all $s \in S$. Thus, t' is the least element of S. □

Corollary 27
$t' \in S$ is a minimal element of S.

Proof. By construction, $t' \in S$ and $t' \leq t$. For any $s \in S$, if $s \leq t$, then $s \in S'$. By the definition of t', we have $t' \leq s$. If $s \notin S'$, then $s > t$, and since $t \geq t'$, it follows that $s > t'$. Therefore, $t' \leq s$ for all $s \in S$.

This shows that t' is the least element of S.

To prove that every finite subset of $\mathbb{N}$ contains a least element, we use mathematical induction. We will show that the well-ordering principle implies the strong form of induction. □

6.2 Connection between the Well-Ordering Principle and Induction

Theorem 28

Assume the well-ordering principle holds. Then the strong form of induction holds too: Suppose $\{P(n)\}_{n\in\mathbb{N}}$ are statements for which:

(a) $P(0)$ is true

(b) $P(0), \dots, P(m-1)$ true $\Rightarrow P(m)$ true for all $m \in \mathbb{N}_{>0}$.

Then $P(n)$ is true for all $n \in \mathbb{N}$.

Proof. Let $S = \{n \in \mathbb{N} : P(n) \text{ is false}\}$. We want to prove that S is empty.

Suppose S is non-empty. Let $t \in S$ be a least element. Since $P(0)$ is true, $0 \notin S$. Therefore, $t \neq 0$, i.e., $t \geq 1$. Since $0, 1, \dots, t-1 < t$, it follows that $0 \notin S, 1 \notin S, \dots, t-1 \notin S$, i.e., $P(0), P(1), \dots, P(t-1)$ are all true. By assumption (b), it follows that $P(t)$ is true, i.e., $t \notin S$. This contradicts $t \in S$.

It follows that S is empty, i.e., $P(n)$ is true for all $n \in \mathbb{N}$. □

The well-ordering principle perspective often reveals what you should take as the base case for an inductive argument.

6.3 Examples

1.
$$\begin{cases} F_0 = 0 \\ F_1 = 1 & \text{for } n \geq 2. \\ F_n = F_{n-1} + F_{n-2} \end{cases}$$

Prove that

$$F_n = \frac{1}{\sqrt{5}}\left(T_+^n - T_-^n\right) \text{ for all } n \in \mathbb{N}.$$

$$T_\pm = \frac{1 \pm \sqrt{5}}{2}, \text{ the roots of } x^2 = x + 1$$

Proof. Let $S = \{n \in \mathbb{N} : F_n \neq \frac{1}{\sqrt{5}}\left(T_+^n - T_-^n\right)\}$. We want to prove that S is empty.

Suppose S is non-empty. Let t be the least element of S.

- Suppose $t \geq 2$. Then
  - (a) $F_{t-1} = \frac{1}{\sqrt{5}}\left(T_+^{t-1} - T_-^{t-1}\right)$ since $t-1 \in \mathbb{N} \setminus S$
  - (b) $F_{t-2} = \frac{1}{\sqrt{5}}\left(T_+^{t-2} - T_-^{t-2}\right)$ since $t-2 \in \mathbb{N} \setminus S$

- Note: We assume $t \geq 2$ here. Otherwise, $t-1$ and $t-2$ are not both natural numbers.

$$\begin{aligned}
F_t &= F_{t-1} + F_{t-2} \quad \text{(by the recursive definition of Fibonacci numbers)} \\
&= \frac{1}{\sqrt{5}}\left(T_+^{t-1} + T_+^{t-2}\right) - \frac{1}{\sqrt{5}}\left(T_-^{t-1} + T_-^{t-2}\right) \\
&= \frac{1}{\sqrt{5}}\left(T_+^{t-2}(T_+ + 1)\right) - \frac{1}{\sqrt{5}}\left(T_-^{t-2}(T_- + 1)\right) \\
&= \frac{1}{\sqrt{5}}\left(T_+^{t-2} \cdot T_+^2\right) - \frac{1}{\sqrt{5}}\left(T_-^{t-2} \cdot T_-^2\right) \\
&= \frac{1}{\sqrt{5}}\left(T_+^t - T_-^t\right)
\end{aligned}$$

Thus, $F_t = \frac{1}{\sqrt{5}}\left(T_+^t - T_-^t\right)$, implying $t \notin S$. This contradicts $t \in S$. It follows that $t = 0$ or $t = 1$.

□

Remark 29. *Three "leftover cases" form our base case, since our main argument above did not address either of these edge cases.*

- If $t = 0$,
$$F_0 = 0 = \frac{1}{\sqrt{5}}\left(T_+^0 - T_-^0\right), \text{ so } 0 \notin S$$
- If $t = 1$,
$$F_1 = 1 = \frac{1}{\sqrt{5}}\left(T_+^1 - T_-^1\right), \text{ so } 1 \notin S$$

We've shown:

- If $t \geq 2$, then t cannot be a least element of S.
- If $t = 0$ or $t = 1$, then $t \notin S$.

Thus, S contains no least element. This contradicts S being non-empty (by the well-ordering principle). It follows that S is empty, i.e.,

$$F_n = \frac{1}{\sqrt{5}}\left(T_+^n - T_-^n\right) \text{ for all } n \in \mathbb{N}$$

This perspective is also helpful for rooting out false statements you might try to prove by induction.

2. Let $P(n)$ be the statement:

$$P(n) : \text{All collections of } n \text{ boxes are the same color.}$$

We know, from life experience, this statement is false.

Let's see why:

Let $S = \{n \in \mathbb{N} : P(n) \text{ is false}\}$.

Suppose S is non-empty. Let t be the least element of S. Suppose $t \geq 3$. Then $P(1)$ and $P(2)$ are true (since $1, 2 \notin S$ by minimality of t). Let $\{1, \ldots, t\}$ be any collection of t boxes. Divide them into two sets

$$A = \{1, \ldots, t-1\} \text{ and } B = \{2, \ldots, t\}$$

Since t is minimal, $P(t-1)$ is true. So all boxes in A are some common color, call it a. Likewise, all boxes in B are some common color, call it b. Since $t \geq 3$, the sets A and B overlap. Thus $a = b$. It follows that $\{1, 2, \ldots, t\}$ are all the same color, i.e., $P(t)$ is true. Thus $t \notin S$, contradicting $t \in S$. Thus, if $t \geq 3$, t cannot be a minimal element of S.

For $t = 1$, $P(1)$ is clearly true. So $1 \notin S$. For $t = 2$, $P(2)$ is not necessarily true. So at this very last step, our argument breaks down!

7 January 24, 2025

7.1 Arithmetic of Z

We turn from counting properties of $\mathbb{Z}$ and $\mathbb{N}$—these feature prominently in induction:

$$0 \underset{\text{next}}{\rightarrow} 1 \underset{\text{next}}{\rightarrow} 2 \underset{\text{next}}{\rightarrow} 3$$

to the basic arithmetic operations in $\mathbb{Z}$: $x, r, \cdots$
What about division?

Definition 30
Let $a, b \in \mathbb{Z}$. We say that b divides a / a is a multiple of b / a is divisible by b if $a = bk$ for some $k \in \mathbb{Z}$. We write that as following

$$b \mid a$$

Example 31
The following could be an example:

- Every integer b divides 0.
- Every integer is divisible by 1.

Fact 32
If $b \neq 0$, then b divides a iff the rational number $\frac{a}{b}$ is actually an integer.

Example 33

$$\frac{50}{7} = 7.14 \quad \text{(not an integer. So 7 does not divide 50.)}$$

7.2 The Division Algorithm

Theorem 34
Let $a, b \in \mathbb{Z}$, $b \neq 0$. Then there exist

- $k \in \mathbb{Z}$
- $r \in \mathbb{Z}$ with $|r| < |b|$

satisfying:

$$a = bk + r$$

Proof. Let $\frac{a}{b} = k + \alpha$ for some $k \in \mathbb{Z}$ and $\alpha \in \mathbb{Q}$ where $0 \leq \alpha < 1$. Multiplying both sides by b, we get:

$$a = kb + \alpha b$$

Define $r = \alpha b$. Then:

$$a = kb + r$$

Since $0 \leq \alpha < 1$, it follows that $0 \leq r < |b|$. Therefore, r is an integer satisfying $0 \leq r < |b|$. Thus, we have:

$$a = kb + r$$

where $k \in \mathbb{Z}$ and $r \in \mathbb{Z}$ with $0 \leq r < |b|$.

$\square$

The result follows.

Remark 35. *In the above proof, we could take $-\frac{1}{2} \leq \alpha \leq \frac{1}{2}$ (as opposed to $0 \leq \alpha < 1$). For $r = a - kb = b\alpha$,*

$$\begin{aligned} |r| &= |\alpha b| \\ &\leq \frac{|b|}{2} \end{aligned}$$

7.3 Common Divisors

Definition 36

Let $a, b \in \mathbb{Z}$. A common divisor d of a and b is an integer $d \in \mathbb{Z}$ for which:

- $d \mid a$
- $d \mid b$

Example 37

Let's consider the following examples:

- $a =$ anything, $b = 0$
$$\left\{\begin{array}{l}\text{common divisors}\\ \text{of } a \text{ and } b = 0\end{array}\right\} = \{\text{divisors of } a\}$$
- $a = 26 = 2 \cdot 13$
$$b = 65 = 5 \cdot 13$$
$$\left\{\begin{array}{l}\text{common divisors}\\ \text{of } 26 \text{ and } 65\end{array}\right\} = \{\pm 1, \pm 13\}$$
- $a = 91, b = 15$
$$\left\{\begin{array}{l}\text{common divisors}\\ \text{of } 91 \text{ and } 15\end{array}\right\} = \{\pm 1\}$$
- $a = 32 = 2 \cdot 2 \cdot 2 \cdot 2 \cdot 2$
$$b = 16 = 2 \cdot 2 \cdot 2 \cdot 2$$
$$\left\{\begin{array}{l}\text{common divisors}\\ \text{of } 32 \text{ and } 16\end{array}\right\} = \{\pm 1, \pm 2, \pm 4, \pm 8, \pm 16\}$$

In all of these examples, observe that there is a common divisor d of a and b divisible by all other common divisors.

Definition 38

$d \in \mathbb{Z}$ is a greatest common divisor of $a, b \in \mathbb{Z}$ if:

1. d is a common divisor of a and b
2. if $e \in \mathbb{Z}$ is a common divisor of a and b, then $e \mid d$.

Lemma 39

Let $a, b \in \mathbb{Z}$. Let e, d be greatest common divisors of a and b. Then $d = \pm e$.

Proof. If a and b both equal 0, then 0 is a greatest common divisor of a and b and is the only one. If not both a and b equal 0, then e and d are necessarily non-zero (since 0 does not divide any non-zero integer).

Since d is a greatest common divisor of a and b, it follows that $d \mid e$. Therefore, there exists some integer $k \in \mathbb{Z}$ such that:

$$e = kd$$

Similarly, since e is also a greatest common divisor of a and b, it follows that $e \mid d$. Therefore, there exists some integer $j \in \mathbb{Z}$ such that:

$$d = je$$

Combining these two equations, we get:

$$d = je = j(kd) = d \cdot jk$$

This implies:

$$d(1 - jk) = 0$$

Since $d \neq 0$, it follows that:

$$1 - jk = 0$$

Hence:

$$jk = 1$$

This means that j and k must be ± 1. Therefore:

$$d = je = \pm e$$

Thus, d and e are equal up to a sign. □

7.4 Euclidean Algorithm

Fact 40

Let $a, b \in \mathbb{Z}$. Then

$$\left\{ \begin{array}{l} \text{common divisors} \\ \text{of } a \text{ and } b \end{array} \right\} = \left\{ \begin{array}{l} \text{common divisors} \\ \text{of } a - b \text{ and } b \end{array} \right\}$$

Proof.

- Suppose d is a common divisor of a and b. Then $a = jd$ and $b = kd$ for some $j, k \in \mathbb{Z}$.

$$\begin{aligned} a - b &= jd - kd \\ &= (j - k)d \\ &\Rightarrow d \text{ divides } a - b \end{aligned}$$

  and

$$b = kd \Rightarrow d \text{ divides } b.$$

Thus, d is a common divisor of $a - b$ and b. It follows that

$$\left\{ \begin{array}{l} \text{common divisors} \\ \text{of } a \text{ and } b \end{array} \right\} \subset \left\{ \begin{array}{l} \text{common divisors} \\ \text{of } a - b \text{ and } b \end{array} \right\}$$

Suppose d divides $a - b$ and b. Then $a - b = jd$ and $b = kd$ for some $j, k \in \mathbb{Z}$.

$$\begin{aligned} a &= (a - b) + b \\ &= jd + kd \\ &\Rightarrow d \text{ divides } a \end{aligned}$$

and

$$b = kd \Rightarrow d \text{ divides } b.$$

- Thus, d is a common divisor of a and b.

$\square$

It follows that

$$\left\{ \begin{array}{l} \text{common divisors} \\ \text{of } a - b \text{ and } b \end{array} \right\} \subset \left\{ \begin{array}{l} \text{common divisors} \\ \text{of } a \text{ and } b \end{array} \right\}$$

Combining the latter two containments:

$$\left\{ \begin{array}{l} \text{common divisors} \\ \text{of } a \text{ and } b \end{array} \right\} = \left\{ \begin{array}{l} \text{common divisors} \\ \text{of } a - b \text{ and } b \end{array} \right\}$$

More generally, the exact same proof technique may be used to prove:

$$\left\{ \begin{array}{l} \text{common divisors} \\ \text{of } a \text{ and } b \end{array} \right\} = \left\{ \begin{array}{l} \text{common divisors} \\ \text{of } a - kb \text{ and } b \end{array} \right\}$$

for every integer k.

7.5 Euclidean Algorithm

Let $CD(a, b)$ denote the set of common divisors of $a, b \in \mathbb{Z}$.

Input: (a, b), $a, b \in \mathbb{Z}$ with $b \neq 0$ and $|b| \leq |a|$.

Output: A pair $(d, 0)$ with

$$CD(a, b) = CD(d, 0)$$

Note:

- Since $d \in CD(d, 0) = CD(a, b)$, d is a common divisor of a and b.
- If $e \in CD(a, b) = CD(d, 0)$, then e divides d and e divides 0.
- Thus, d is a greatest common divisor of a and b.

The Algorithm:

1. If $b = 0$, return $(a, 0)$.

2. Otherwise, find $A \in \mathbb{Z}$ for which

$$r = a - Ab \text{ satisfies } |r| < |b|.$$

(By the division algorithm, this is always possible)

3. Replace (a, b) by $(a^*, b^*) := (b, r)$.

   - Go to (1) if $b^* = 0$
   - Go to the start of step (2) if $b^* \neq 0$

Proposition 41

The Euclidean algorithm terminates.

Proof. Let (a_n, b_n) be the n^{th} pair calculated in the process of running the Euclidean algorithm. The pair

$$(a_0, b_0), (a_1, b_1), (a_2, b_2), \ldots (a, b)$$

satisfy:

- $|a_m| \geq |b_m|$
- $(a_{m+1}, b_{m+1}) = (a_m^*, b_m^*)$

By construction,

$$|b_m^*| < |b_m|.$$

So $|b_0| > |b_1| > \ldots$ is a strictly decreasing sequence of natural numbers. Therefore, the sequence must terminate at by going to step (1) and outputting $(a_n, b_n) = (a_n, 0)$ for some (finite) $n \in \mathbb{N}$. This proves the algorithm terminates. $\square$

Remark 42. *Given $x, y \in \mathbb{Z}$, we've seen that we can find $A \in \mathbb{Z}$ for which $r = x - Ay$ satisfies $|r| \leq |y|/2$. Applying this choice of r consistently throughout the running of the Euclidean algorithm, Euclidean_Algorithm(a, b) runs in time $O(\log_2 |b|)$.*

7.6 Examples

1. Let's find the gcd of 576 and 243.

$$\begin{aligned}(576, 243) &= (243, 576 - 2 \cdot 243)\\ &= (243, 90)\\ &= (90, 243 - 2 \cdot 90)\\ &= (90, 63)\\ &= (63, 90 - 1 \cdot 63)\\ &= (63, 27)\\ &= (27, 63 - 2 \cdot 27)\\ &= (27, 9)\\ &= (9, 27 - 3 \cdot 9)\\ &= (9, 0)\end{aligned}$$

   Thereofore,

$$\gcd(576, 243) = 9$$

2. Let's find the gcd of 101 and 66.

$$\begin{aligned}(101, 66) &= (66, 101 - 1 \cdot 66)\\ &= (66, 35)\\ &= (35, 66 - 1 \cdot 35)\\ &= (35, 31)\\ &= (31, 35 - 1 \cdot 31)\\ &= (31, 4)\\ &= (4, 31 - 7 \cdot 4)\\ &= (4, 3)\\ &= (3, 4 - 1 \cdot 3)\\ &= (3, 1)\\ &= (1, 3 - 3 \cdot 1)\\ &= (1, 0)\end{aligned}$$

   Thereofore,

$$\gcd(101, 66) = 1$$

3. Let's find the gcd of 104 and 80.

$$
\begin{aligned}
(104, 80) &= (80, 104 - 1 \cdot 80) \\
&= (80, 24) \\
&= (24, 80 - 3 \cdot 24) \\
&= (24, 8) \\
&= (8, 24 - 3 \cdot 8) \\
&= (8, 0)
\end{aligned}
$$

Thereofore,

$$\gcd(104, 80) = 8$$

8 January 29, 2025

We describe an enhanced version of the Euclidean algorithm that allows us to solve the equation

$$xa + yb = d \quad \text{for} \quad x, y \in \mathbb{Z}, \quad d = \gcd(a, b)$$

Proposition: Let $a, b \in \mathbb{Z}$. Suppose there are integers $x, y \in \mathbb{Z}$ for which

Proposition 43

$$x \cdot a + y \cdot b = d$$

for some common divisor d of a and b. Then d is a greatest common divisor of a and b.

Proof. By assumption, d is a common divisor of a and b.

- Suppose $e \mid a$ and $e \mid b$. Then

$$e \mid xa \quad \text{and} \quad e \mid yb \implies e \mid (xa + yb) = d.$$

It follows that d is a greatest common divisor of a and b. □

8.1 The Algorithm

Let $a, b \in \mathbb{Z}$ with $|a| \geq |b|$.

1. Form a 3-column table:

d	x	y

2. Initialize the first two rows as:

e	x	y
a	1	0
b	0	1

3. Note: $xa + yb = e$ where (e, x, y) forms a row in this table.

4. Run the Euclidean algorithm in the left column of the table:

e	x	y
e'	x'	y'
e''	x''	y''

In particular,

$$e' = x'a + y'b$$
$$e'' = x''a + y''b$$

By the division algorithm, we can find $k \in \mathbb{Z}$ for which $e''' := e' - ke''$ satisfies $|e'''| \leq |e''|$.

Add the new bottom row

$$R''' := R' - kR''$$

to our table:

e	x	y
e'	x'	y'
e''	x''	y''
e'''	x'''	y'''

Note that the relation $x'''a + y'''b = e'''$ holds for the new bottom row of our table too, since it holds for the second-to-bottom and third-to-bottom rows too:

$$\begin{aligned} x'''a + y'''b &= (x' - kx'')a + (y' - ky'')b \\ &= (x'a + y'b) - k(x''a + y''b) \quad \text{(regrouping terms)} \\ &= e' - k \cdot e'' \\ &= e''' \end{aligned}$$

5. Stop adding new rows once the bottom two rows become.

By the theory of the Euclidean algorithm,

$$d = \gcd(a, b)$$

Furthermore, since $xa + yb = e$ for every row (e, x, y) from our table, it follows that

$$x_0 \cdot a + y_0 \cdot b = d$$

Problem 44

Consider the following problems:

- Prove that $\gcd(x_1, y_1) = 1$.
- (HARD) Prove that $a = \pm d \cdot y_1$ and $b = \mp d \cdot x_1$.

8.2 Examples

1. Extended Euclidean algorithm for $(596, 243)$:

e	x	y
596	1	0
243	0	1
90	1	-2
63	-2	5

2. Extended Euclidean algorithm for $(3587, 1819)$:

e	x	y
3587	1	0
1819	0	1
-51	1	-2
34	35	-69
-17	36	-71
0	107	-211

We read off:

$$\begin{cases} -17 = 36 \times 3587 + (-71) \times 1819 & \text{(from the next to last row)} \\ 3587 = 17 \times 211 \\ 1819 = 17 \times 107 \end{cases}$$

9 January 31, 2025

We proved:

Proposition 45
Let $a, b \in \mathbb{Z}$. Let $d = \gcd(a, b)$. There exist integers $x, y \in \mathbb{Z}$ such that

$$xa + yb = d.$$

Not only did we prove this abstract existence statement, but we saw how to extract x, y from the output of the Extended Euclidean Algorithm.

9.1 Ideals in the set of Real Numbers

$I = \{xayb : x, y \in \mathbb{Z}\} \subset \mathbb{Z}$ is an ideal in the ring $\mathbb{Z}$ if and only if:

- I is closed under $+$, $-$, and $0 \in I$.
- $r \cdot i \in I$ for all $i \in I$ and $r \in \mathbb{Z}$.

The above proposition showed that every ideal in $\mathbb{Z}$ consists of multiples of a single element. Thus, $\mathbb{Z}$ is a so-called principal ideal domain. More on this later.

9.2 An important application of the above proposition:

Lemma 46
Let $a, b \in \mathbb{Z}, n \in \mathbb{Z}$ with $n \neq 0$. Suppose

- $n \mid ab$
- $\gcd(a, n) = 1$.

Then $n \mid b$.

Proof. Since $\gcd(a, n) = 1$, we can find integers x, y such that

$$1 = x \cdot a + y \cdot n$$

Multiply both sides of (f) by b:

$$\begin{aligned} b &= (x \cdot a + y \cdot n) \cdot b \\ &= x \cdot (ab) + (yb) \cdot n \Rightarrow b \text{ is a multiple of } n \text{ by (i).} \end{aligned}$$

□

9.3 Application to primes and prime factorization

Definition 47
Let $p \in \mathbb{Z}, p \leq -1$. p is prime if

$$\{\text{divisors of } p\} = \{\pm 1, \pm p\}.$$

Example 48
- Prime: $2, 3, 5, 7, 11, 13, 17, 19, \dots$
- Not prime: $4 = 2 \times 2, 6 = 2 \times 3, 9 = 3 \times 3, 91 = 13 \times 7$

Fact 49
Non-prime integers are otherwise known as composite.

9.4 Sieve of Eratosthenes

(An algorithm to list all primes in $\{2, 3, \dots, N\}$)

1. Begin with $L = \{2, 3, \dots, N\}, P = \phi$.
2. Add the smallest element s of L to P and then remove s and all of its multiples from L.
3. Continue doing this until all elements are removed from L.

Problem 50
The final P consists of all prime numbers in $\{2, \dots, N\}$.

9.5 Factorization into primes

Proposition 51
Let $n \in \mathbb{N}$ with $n \neq 0$. Then n factors as a product of primes.

Proof. We prove this by induction on n.
Base case: $n = 1$. Then $n = 1$ is the empty product of primes.
Inductive step: Let $m \geq 2$. Suppose that for $1 \leq k < m$, k can be expressed as a product of primes.

- If m is prime, $m = m$ expresses m as a product of 1 prime.
- If m is not prime, $m = ab$ for some $1 < a, b < m$.

Since $1 \leq a = m/b < m$ and $1 \leq b = m/a < m$, we can express a and b as products of primes:

$$a = p_1 \dots p_j \quad p_1, \dots, p_j \text{ prime}$$
$$b = q_1 \dots q_t \quad q_1, \dots, q_t \text{ prime}$$

Then $m = ab = (p_1 \dots p_j)(q_1 \dots q_t)$ expresses m as a product of primes, thus completing the inductive step.

It follows, by induction, that every integer $n \geq 1$ can be expressed as a product of primes. □

As an application, we can prove the infinitude of primes:

Theorem 52

There are infinitely many primes $p \in \mathbb{Z}$.

Proof. Let $n \in \mathbb{Z}_{>1}$.

Consider $n! + 1$, where $n! = n \times (n-1) \times \dots \times 2 \times 1$.

Since $n!$ is a product of integers from 1 to n, any prime factor p of $n! + 1$ must satisfy $p \mid n! + 1$.

Claim: $p > n$.

Suppose for contradiction that $p \leq n$.

Since $p \leq n$, p must divide $n!$. Therefore, $p \mid n!$.

But $p \mid n! + 1$ and $p \mid n!$ imply $p \mid (n! + 1) - n! = 1$, which is a contradiction since no prime number divides 1.

Hence, $p > n$ as claimed.

Therefore, for every $n \in \mathbb{Z}_{>1}$, there exists a prime number $p > n$. This implies that there are infinitely many primes. □

9.6 An important characterization of primes

Theorem 53

$p \in \mathbb{Z}$ is prime $\Leftrightarrow$ for all $a, b \in \mathbb{Z}$, $p \mid ab$ implies $p \mid a$ or $p \mid b$.

Proof. ($\Leftarrow$) Suppose p is not prime. Then $p = ab$ for some $a, b \in \mathbb{Z}$ with $a, b \neq \pm 1$. Then $p \mid p = ab$ but $p \nmid a$ and $p \nmid b$.

($\Rightarrow$) Suppose p is prime. Suppose $p \mid ab$. Note that

$$\left\{ \begin{array}{l} \text{common divisors} \\ \text{of } a \text{ and } p \end{array} \right\} \subset \left\{ \begin{array}{l} \text{divisors of} \\ p \end{array} \right\} = \{\pm 1, \pm p\}$$

Since $\pm p$ are not divisors of a,

$$\left\{ \begin{array}{l} \text{common divisors} \\ \text{of } a \text{ and } p \end{array} \right\} = \{\pm 1\}, \text{ i.e., } \gcd(a, p) = \pm 1$$

By our earlier key lemma, since $p \mid ab$ and $\gcd(a, p) = \pm 1$, it follows that $p \mid b$. □

Theorem 54

Let $p \in \mathbb{Z}$ be prime. Let $a_1, \dots, a_n \in \mathbb{Z}$ be integers for which $p \mid a_1 \dots a_n$. Then $p \mid a_1$ or $p \mid a_2 \dots a_n$.

Proof. We prove this by induction on n.

Base case: $n = 2$. This is the previous case, which states that if $p \mid a_1 a_2$, then $p \mid a_1$ or $p \mid a_2$.

Inductive step: Suppose the statement is true for some $n \geq 2$. That is, if $p \mid a_1 \dots a_n$, then $p \mid a_1$ or $p \mid a_2 \dots a_n$.

We need to show that the statement is true for $n + 1$. Suppose $p \mid a_1 a_2 \dots a_n a_{n+1}$. By the inductive hypothesis, applied to the product $a_1 a_2 \dots a_n$, we have $p \mid a_1$ or $p \mid a_2 \dots a_n$.

- If $p \mid a_1$, we are done.
- If $p \mid a_2 \dots a_n$, then by the base case applied to the product $(a_2 \dots a_n)a_{n+1}$, we have $p \mid a_2 \dots a_n$ implies $p \mid a_2$ or $p \mid a_3 \dots a_n$.

Continuing this process, we eventually conclude that $p \mid a_1$ or $p \mid a_2$ or $\dots$ or $p \mid a_{n+1}$.

Therefore, by induction, the statement is true for all $n \geq 2$. $\square$

We use the latter characterization of primes to prove uniqueness of prime factorization.

Theorem 55

Every integer $n \neq 0$ can be written in a unique way as a product of primes.

More formally, if

$$n = p_1^{e_1} \cdots p_k^{e_k} \quad p_1, \dots, p_k \text{ distinct primes } e_1, \dots, e_k \in \mathbb{Z}_{\geq 1}$$
$$n = q_1^{f_1} \cdots q_l^{f_l} \quad q_1, \dots, q_l \text{ distinct primes } f_1, \dots, f_l \in \mathbb{Z}_{\geq 1}$$

Then $k = l$ and $(q_1, \dots, q_l)$ is a rearrangement of $(p_1, \dots, p_k)$, i.e., $q_i = p_{\sigma(i)}$ for some bijection $\sigma : \{1, \dots, k\} \to \{1, \dots, k\}$ and $f_j = e_{\sigma(j)}$.

Proof. We prove this by induction on n.

Base case: $n = 1$. $n = 1$ can only be factored as the empty product over primes. Thus, its factorization into primes is unique.

Inductive step: Let $m \geq 2$. Suppose every $1 \leq k < m$ can be factored uniquely as a product of primes.

Suppose

$$m = p_1^{e_1} \cdots p_k^{e_k} \quad p_1, \dots, p_k \text{ distinct primes } e_1, \dots, e_k \in \mathbb{Z}_{\geq 1}$$
$$m = q_1^{f_1} \cdots q_l^{f_l} \quad q_1, \dots, q_l \text{ distinct primes } f_1, \dots, f_l \in \mathbb{Z}_{\geq 1}$$

are two factorizations of m. Let $p = p_1$.

By (i), $p \mid m$. By (ii), $p \mid m = q_1^{f_1} \cdots q_l^{f_l}$. By our product characterization of primes, (i) implies $p \mid q_1$ or $\dots$ or $p \mid q_l$.

Since the q's are prime, $p \mid q_i$ is equivalent to $p = q_i$.

Thus, $p = q_1$ or $\dots$ or $p = q_l$.

Suppose WLOG that $p_1 = p = q_1$.

Then

$$m/p = p_1^{e_1 - 1} p_2^{e_2} \cdots p_k^{e_k} = q_1^{f_1 - 1} q_2^{f_2} \cdots q_l^{f_l}$$

Continuing by the same argument (and letting q_1 play the role of p_1 too), we can prove that

$$p_1 = p = q_1$$
$$e_1 = f_1$$

Consider

$$m/p^{e_1} = p_2^{e_2} \cdots p_k^{e_k}$$
$$m/q_1^{f_1} = q_2^{f_2} \cdots q_l^{f_l}$$

By inductive hypothesis (since $1 \leq m/p^{e_1} < m$),

$$k - 1 = l - 1$$
$$= (q_2, \ldots, q_l) \text{ is a rearrangement of } (p_2, \ldots, p_k) \text{ via a bijection } \sigma : \{2, \ldots, k\} \to \{2, \ldots, k\}$$
$$q_j = p_{\sigma(j)} \text{ for } j = 2, \ldots, l$$
$$f_j = e_{\sigma(j)} \text{ for } j = 2, \ldots, k$$

The inductive step follows from this:

$$k - 1 = l - 1 \Rightarrow k = l$$
$$= (q_2, \ldots, q_l) \text{ a rearrangement of } (p_2, \ldots, p_k) \text{ via } \sigma : \{2, \ldots, k\} \to \{2, \ldots, k\}$$
$$\Rightarrow (q_1, \ldots, q_l) \text{ is a rearrangement of } (p_1, \ldots, p_k) \text{ via } \tilde{\sigma} : \{1, 2, \ldots, k\} \to \{1, 2, \ldots, k\}$$
$$\tilde{\sigma}(x) = \begin{cases} \sigma(x) \text{ if } x \neq 1 \\ 1 \quad \text{if } x = 1 \end{cases}$$
$$f_j = e_{\sigma(j)} \text{ for } j = 2, \ldots, k$$
$$\Rightarrow f_j = e_{\sigma(j)} \text{ for } j = 1, \ldots, k \quad (\text{since } \sigma(1) = 1).$$

By induction, unique factorization in $\mathbb{Z}$ follows. □

10 February 3, 2025

We abstract the properties we need for arithmetic in:

10.1 Grade School Algorithm for Multiplication

$$123 + 5 = ((100 + 1 + 10 + 2) + 1 + 3) + 5$$
$$= (100 \times 1 + 10 \times 2) + 5 + (1 + 3) + 5$$
$$= (100 + 1) + 5 + (10 \times 2) + 5) + (+3) + 5$$
$$= (100 \times (1 \times 5) + 10 + (2 \times 5)) + (0 + 1 + 1 + 5)$$
$$= ((100 + (1 \times 5) + 10 + (2 \times 5)) + 10 + 1) + 1 \times 5$$

$$= (100 + (1 \times 5) + (10 + (2 \times 5) + 10 + 1)) + 115$$

$$= (100 \times (1 \times 5) + 10 + (2 + 5 + 1)) + 15$$

$$= (100 + (1 + 5) + 10 + (11)) + 1\times$$

$$= (100 + ((\times 5) + 10 \times (10 + 1)) + 1$$

$$= (100 + (1 \times 5) + (10 + 10 + 10 \times 1)) + 1$$

$$= (100 + (1 \times 5) + (100 + 1) + 10 + 1) + 1\times$$

$$= (100 + (1 \times 5) + 100 \times 1) + 10 \times 1) + 1 + 5$$

$$= (100 \times (1 \times 5 + 1) + 10 + 1) + 15$$

$$= (100 + 6 + 10 + 1) + 1 + 5$$

$$= 615$$

Tracing through, we repeatedly used:

- $(a + b) + c = a + (b + c)$
- $(a \cdot b) \cdot c = a \cdot (b \cdot c)$
- $(a + b) \cdot c = a \cdot c + b \cdot c$

These form the basis for the ring axioms.

10.2 Definition: Ring

A ring $(R, +, \cdot, 0, 1)$ is a set R equipped with binary operations $+ : R \times R \to R$ and $\cdot : R \times R \to R$, and elements $0, 1 \in R$ subject to the following axioms:

10.2.1 Addition-only

(A1) $(a + b) + c = a + (b + c)$ for all $a, b, c \in R$

(A2) $a + 0 = 0 + a = a$ for all $a \in R$

(A3) For every $a \in R$, there exists an element $-a \in R$ satisfying:

$$a + (-a) = (-a) + a = 0$$

(A4) $a + b = b + a$ for all $a, b \in R$

10.2.2 Multiplication-only

(M1) $(a \cdot b) \cdot c = a \cdot (b \cdot c)$ for all $a, b, c \in R$

(M2) $a \cdot 1 = 1 \cdot a = a$ for all $a \in R$

(M3) $a \cdot b = b \cdot a$ for all $a, b \in R$

10.2.3 Distributive Properties

(D1) $(a+b)\cdot c = a\cdot c + b\cdot c$ for all $a, b, c \in R$

(D2) $a\cdot(b+c) = a\cdot b + a\cdot c$ for all $a, b, c \in R$

10.3 Remark

The axioms above will always be our default ring axioms. Be aware, however, that in some contexts, it is natural to assume/not assume (M2) and to assume/not assume (M3). The result is $2\times 2 = 4$ different types of rings:

- $(M2), (M3)$: Commutative ring with 1
- $(M2), (\neg M3)$: Non-commutative ring with 1
- $(\neg M2), (M3)$: Commutative ring without 1
- $(\neg M2), (\neg M3)$: Non-commutative ring without 1

As noted above, we assume our rings to be of $(M2), (M3)$ type, i.e., commutative rings with 1, unless otherwise stated.

10.4 Examples

1. $(\mathbb{Z}, +, \cdot, 0, 1)$, the integers with their usual operations of addition, multiplication, and 0, 1, are a ring.
2. Let $n \geq 2$, $n \neq 0, 1$. Define $\mathbb{Z}/n\mathbb{Z}$ to be the set of equivalence classes for $\mathbb{Z}$ equipped with the equivalence relation:

   $$a \sim b \iff a - b \text{ is a multiple of } n.$$

   Let $[a]$ denote the equivalence class represented by a.

   We equip $\mathbb{Z}/n\mathbb{Z}$ with two binary operations:

   $$[a] + [b] := [a+b]$$

   and

   $$[a]\cdot[b] := [a\cdot b].$$

   Claim: The latter operations are well-defined, i.e., if $[a] = [a']$ and $[b] = [b']$, then

   $$[a' + b'] = [a+b]$$

   and

   $$[a'\cdot b'] = [a\cdot b].$$

   Proof: Since $[a] = [a']$ and $[b] = [b']$, we have

   $$a' = a + jn \quad \text{and} \quad b' = b + kn$$

for some $j, k \in \mathbb{Z}$. Note that

$$a' + b' = a + b + (j + k)n$$

and

$$a' \cdot b' = (a + jn) \cdot (b + kn) = a \cdot b + (a \cdot k + b \cdot j + j \cdot k \cdot n)n.$$

Thus,

$$[a' + b'] = [a + b]$$

and

$$[a' \cdot b'] = [a \cdot b]$$

as claimed.

$\mathbb{Z}/n\mathbb{Z}$ equipped with the latter binary operations and $0 := [0]$, $1 := [1]$ is a ring.

Proof: We'll check just (D1) to give a flavor of how this is proved. (All other ring axioms are proved similarly.)

$$([a] + [b]) \cdot [c] = [a + b] \cdot [c] = [(a + b) \cdot c] = [(a \cdot c) + (b \cdot c)]$$

by (D1) in the ring $\mathbb{Z}$. Thus,

$$[a \cdot c] + [b \cdot c] = [a] \cdot [c] + [b] \cdot [c].$$

11 February 5, 2025

11.1 Examples of Rings

Last time we we defined abstract rings.

Remark 56. $1 \in \mathbb{R}$ *(ring with* 1

Fact 57

If you take the set of all integers, and you add and multiply them, you get a ring.

11.1.1 Non-commutative Rings

1. Let V be a vector space over $\mathbb{R}$. The set $S = \{\text{linear transformations } T : V \to V\}$ forms a ring with addition and composition of transformations. For $T, T' \in S$, the addition $T + T'$ is defined by $(T + T')(v) := T(v) + T'(v)$ for all $v \in V$.

2. The zero ring is a ring in which the product of any two elements is zero. It can be defined as $R = \{0\}$ with the operations $0 + 0 = 0$ and $0 \cdot 0 = 0$. This ring has only one element, which is both the additive and multiplicative identity.

3. If T, T' are both linear transformations from $V \to V$. Then $T \cdot T' = T \cdot T' = ((T \cdot T)(v)) = T(T'(x))$. That means that the composition of two linear transformations is also a linear transformation.

Fact 58

If we take two matrices T, T' and multiply them together $T \cdot T'$ and $T' \cdot T$ then they are not the sample. For example

$$T = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}$$

and

$$T' = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$$

$$T \cdot T' = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$$

and

$$T' \cdot T = \begin{vmatrix} 1 & 0 \\ 0 & 0 \end{vmatrix}$$

Therefore, we proved that composition of two linear transformations is not commutative. However, the distributive properties hold.

12 February 7, 2025

12.1 Example of using the ring axioms

Let R be a ring.

1. The additive identity element $O \in R$ is unique, i.e., if $O' \in R$ is a second element satisfying $a + O' = O' + a = a$ for all $a \in R$, then $O = O'$.
2. Additive inverses in R are unique, i.e., if $b + a = a + b = 0$ and $b' + a = a + b' = 0$, then $b = b'$.
3. Additive inverses in R are unique, i.e., if $b + a = a + b = 0$ and $b' + a = a + b' = 0$, then $b = b'$.

12.1.1 Proof:

Consider

$$c = (b' + a) + b \Rightarrow \text{associative law for } +$$

$$= b' + (a + b)$$

Using the first expression:

$$c = (b' + a) + b$$
$$= 0 + b$$
$$= b \Rightarrow b = b'$$

Using the second:

$$
\begin{aligned}
c &= b' + (a + b) \\
&= b' + 0 \\
&= b'
\end{aligned}
$$

12.2 Exercise:

Suppose R is a ring with 1.

1. Prove that the multiplicative identity element 1 is unique.
2. Suppose $a \in R$ admits a multiplicative inverse b. Then b is unique.
3. $a \cdot 0 = 0 \cdot a = 0$ for all $a \in R$.

12.2.1 Proof for (3):

$$a \cdot 0 = a \cdot (0 + 0) \quad \text{since } 0 = 0 + 0$$

$$= a \cdot 0 + a \cdot 0 \quad \text{by the distributive axiom}$$

By the axioms for addition in R, $a \cdot 0$ admits a (unique) additive inverse b. Adding b to both sides:

$$
\begin{aligned}
0 &= a \cdot 0 + b \\
&= (a \cdot 0 + a \cdot 0) + b \\
&= a \cdot 0 + (a \cdot 0 + b) \quad \text{associativity of } + \\
&= a \cdot 0 + 0 \\
&= a \cdot 0
\end{aligned}
$$

Thus,

$$a \cdot 0 = 0$$

The proof that $0 \cdot a = 0$ for all $a \in R$ is almost identical.

12.2.2 Proof for $a \cdot (-b) = -ab$:

$$(-a) \cdot b = -ab \quad \text{for all } a, b \in R$$

Consider:

$$(-a) \cdot b + a \cdot b$$

$$= ((-a) + a) \cdot b \quad \text{distributive axiom}$$

$$= 0 \cdot b$$

$$= 0 \quad \text{by (3)}$$

Adding $-ab$ to both sides of the above:

$$\begin{aligned} 0 + (-ab) &= ((-a) \cdot b + a \cdot b) + (-ab) \\ &= (-a) \cdot b + (ab + (-ab)) \quad \text{associativity of } + \\ &= (-a) \cdot b + 0 \\ &= (-a) \cdot b \end{aligned}$$

Thus, $(-a) \cdot b = -ab$.

Proving $a \cdot (-b) = -ab$ is entirely similar.

12.2.3 Proof for $(-a)(-b) = ab$:

$$(-a)(-b) = ab \quad \text{for all } a, b \in R$$

Consider:

$$(-a)(-b) = -(a(-b)) \quad \text{by (4)}$$

$$= -(-ab) \quad \text{by (4)}$$

$$= ab$$

Since $ab + (-ab) = 0$,

$$-(-ab) = ab$$

Thus, $(-a)(-b) = ab$ for all $a, b \in R$.

12.3 Subrings

12.3.1 Definition:

Let $S \subset R$ be a subset. It is a subring if S, with ring operations inherited from those of R, is itself a ring.

12.3.2 Note:

For any subset $S \subset R$, the ring operations on R induce mappings:

$$+ : S \times S \longrightarrow R$$

$$\cdot : S \times S \longrightarrow R$$

Subrings are distinguished by: the above mappings factor through the inclusion $S \subset R$:

$$+ : S \times S \longrightarrow S$$

$$\cdot : S \times S \longrightarrow S$$

12.3.3 Lemma:

Let R be a ring. Let $S \subset R$ be a non-empty subset. Then $S \subset R$ is a subring iff it is closed under multiplication and subtraction, i.e.,

$$s_1 - s_2 \,(:= s_1 + (-s_2)) \in S \text{ for all } s_1, s_2 \in S$$
$$s_1 \cdot s_2 \in S \text{ for all } s_1, s_2 \in S$$

12.3.4 Proof:

($\Rightarrow$) Follows from the definition of ring.

($\Leftarrow$) Since S is non-empty, $s_0 \in S$ for some $s_0 \in R$. Then $0 = s_0 + (-s_0) \in S$. Also, for all $s \in S$, $0 + (-s) \in S$.

$$\therefore \quad s_1 + s_2 = s_1 - (-s_2) \in S \text{ for all } s_1, s_2 \in S$$

It follows that the ring operation on S induced by those on R factor through S:

$$+_0 : S \times S \to S \quad (\subset R)$$
$$\cdot_0 : S \times S \to S \quad (\subset R)$$

The ring axioms on S follow from those on R, e.g., let $a, b, c \in S$.

$$(a + b) \cdot c = a \cdot c + b \cdot c \quad \text{by the distributive axiom in } R$$

But instead of interpreting this as an equality in R, we interpret it as an equality in S (which we may do since S is closed under $+$ and $\cdot$ in R).

12.4 Examples of subrings

1. $\mathbb{Z} \subset \mathbb{Q} \subset \mathbb{R} \subset \mathbb{C}$ (integers, rational numbers, real numbers, and complex numbers all equipped with their usual $+$ and $\cdot$). $\mathbb{Z} \subset \mathbb{Q}$ is a subring, $\mathbb{Q} \subset \mathbb{R}$ is a subring, $\mathbb{R} \subset \mathbb{C}$ is a subring, $\mathbb{Z} \subset \mathbb{R}$ is a subring, $\mathbb{Z} \subset \mathbb{C}$ is a subring, $\mathbb{Q} \subset \mathbb{C}$ is a subring.
2. $\mathbb{Z}[i] := \{a + bi : a, b \in \mathbb{Z}\} \subset \mathbb{C}$.

12.4.1 Claim:

$\mathbb{Z}[i] \subset \mathbb{C}$ is a subring.

12.4.2 Proof:

Let $a, b, c, d \in \mathbb{Z}$.

$$(a + bi) - (c + di) = (a - c) + (b - d)i \in \mathbb{Z}[i]$$
$$(a + bi) \cdot (c + di) = (ac - bd) + (ad + bc)i \in \mathbb{Z}[i]$$

Since $\mathbb{Z}[i] \subset \mathbb{C}$ is closed under subtraction and multiplication, it is a subring.

12.4.3 Terminology:

$\mathbb{Z}[i]$ is called the Gaussian integers.

3. $\mathbb{H}$ = Hamilton quaternions

$$= \{a + bi + cj + dk : a, b, c, d \in \mathbb{R}\}$$

Addition is coordinate-wise. Multiplication is determined by the table:

$$\begin{array}{lll} i^2 = -1 & ij = k & ji = -ij = -k \\ j^2 = -1 & jk = i & kj = -jk = -i \\ k^2 = -1 & ki = j & ik = -ki = j \end{array}$$

together with $\mathbb{R}$-bilinearity.

Let $\mathcal{O} = \{a + bi + cj + dk : a, b, c, d \in \mathbb{Z}\}$.

12.4.4 Claim:

$\mathcal{O} \subset \mathbb{H}$ is a subring.

12.4.5 Proof:

$\mathcal{O}$ is clearly closed under subtraction.

For every pair $\alpha, \beta \in \{1, \pm i, \pm j, \pm k\}$, the above multiplication table shows that

$$\alpha\beta \in \{1, \pm i, \pm j, \pm k\} \subset \mathcal{O}$$

Closure under multiplication follows from this, e.g.,

$$\begin{aligned} (2i + 3j) \cdot (5j + 7k) &= 2 \cdot 5(ij) + 2 \cdot 7(ik) + 3 \cdot 5(jj) + 3 \cdot 7(jk) \\ &= 2 \cdot 5k + 2 \cdot 7(-j) + 3 \cdot 5(-1) + 3 \cdot 7i \\ &= -3 \cdot 5 + 3 \cdot 7 + (-2 \cdot 7)j + 2 \cdot 5k \\ &\in \mathcal{O} \end{aligned}$$

Thus, $\mathcal{O} \subset \mathbb{H}$ is a subring.

4. $A = \{f : \mathbb{R} \to \mathbb{R} : f \text{ continuous}\}$

Ring operations:

- $+$: pointwise addition of functions
- $\cdot$: pointwise multiplication of functions

$A' = \{f : \mathbb{R} \to \mathbb{R} : f \text{ continuous and compactly supported}\}$

A' is closed under $-$ and $\cdot$, i.e., the difference of compactly supported functions is compactly supported, and the product of compactly supported functions is compactly supported.

Thus, $A' \subset A$ is a subring.

13 February 10, 2025

13.1 Domains and Fields

Definition 59 (Ring)
Let $\mathbb{R}$ be a ring. The element $0 \neq b \in \mathbb{R}$ is a **zero divisor** if there exists some $0 \neq c \in \mathbb{R}$ with $bc = 0$.

Definition 60 (Integral Domain)
Let $\mathbb{R}$ be a ring. $\mathbb{R}$ is a **domain** (or **integral domain**) if it admits no zero divisors.

Example 61
The set of real numbers $\mathbb{R}$ and integers $\mathbb{Z}$ is a domain if for $ab = 0$, for $a, b \in \mathbb{Z}$ then $a = 0$ or $b = 0$

Definition 62 (Invertibility)
Let $\mathbb{R}$ be a ring with 1. An element $b \in \mathbb{R}$ is **invertible** if there exists some $c \in \mathbb{R}$ for which $bc = cb = 1$. We let $R^x = b \in RR : b$ is invertible

Let A be the ring of 2×2 matrices with coefficients in $\mathbb{R}$, with the usual addition and multiplication of 2×2 matrices. A is a non-commutative ring with identity. Let A' be the set of invertible 2×2 matrices. Then $I \in A$, but $I \notin A'$. Suppose $Z = a + bi \in \mathbb{C}$ is invertible, i.e., $ZB = 1$ for some $B = c + di \in \mathbb{C}$. Then:

$$\bar{Z}B = \bar{Z} \cdot B = 1 \quad (\text{where}\,^{-}\text{denotes complex conjugation})$$

$$= \bar{B}Z = B\bar{Z} \quad (\text{since } \mathbb{C} \text{ is commutative})$$

$$= (a - bi)(c + di) = (a + b^2)(c^2 + d^2) = 1$$

It follows that:

$$(a, b) = (1, 0) \text{ or } (0, 1)$$

corresponding to 1 and i. Thus, $\mathbb{C} = \{a + bi : a, b \in \mathbb{R}\}$. $\mathbb{C}$ is much more interesting:

$$\mathbb{C} = \{a + bi : a, b \in \mathbb{R}\}$$

Definition 63 (invertible Ring)

Let R be a ring with 1. If all non-zero elements of R are invertible, i.e., $R' = R \setminus \{0\}$, then R is a field if R is commutative, or a skew field if R is non-commutative.

Example 64

The following are fields:

- $\mathbb{Q}$ (skew) are all subrings of fields.
- $\mathbb{R}, \mathbb{C}, \mathbb{H}$ are necessarily integral domains.
- $\mathbb{H}$ (Hamilton's quaternions) $= \{a + bi + cj + dk : a, b, c, d \in \mathbb{R}\}$ with multiplication determined by $\mathbb{R}$-bilinearity and:

$$i^2 = -1, \quad ij = k, \quad ji = -k,$$
$$j^2 = -1, \quad jk = i, \quad kj = -i,$$
$$k^2 = -1, \quad ki = j, \quad ik = -j$$

  $\mathbb{H}$ is a skew field.

Lemma 65

Let A be a subring of a field F. Then A is an integral domain.

Proof. Suppose $x, y \in A$ and $xy = 0$ in A. Then $y = 0$ in F too. Suppose $x \neq 0$ in A, so $x \neq 0$ in F too. Multiply both sides of $xy = 0$ by $x^{-1} \in F$:

$$x^{-1}(xy) = x^{-1} \cdot 0 = 0$$
$$(x^{-1}x)y = y = 0 \quad \text{in } F$$

Thus, $y = 0$ in A. Therefore, A is a domain. $\square$

Example 66

The following are also fields:

- $\mathbb{Q}$ (skew) are all subrings of fields.
- $\mathbb{R}, \mathbb{C}, \mathbb{H}$ are necessarily integral domains.

14 February 12, 2025

14.1 Matrices

Let A be the ring of 2×2 matrices with coefficients in $\mathbb{R}$. The operations $+$ and $\cdot$ are the usual addition and multiplication of 2×2 matrices.

Consider the matrix $t = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$.

We have:

$$t \cdot t = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$$

Thus, t is a zero divisor, and therefore A is not a domain.

14.2 Continuous Functions

Let A be the set of continuous functions $f : \mathbb{R} \to \mathbb{R}$ with pointwise addition and multiplication.

Consider two continuous functions f and g such that for every $x \in \mathbb{R}$, either $f(x) = 0$ or $g(x) = 0$.

The product $(f \cdot g)(x) = f(x) \cdot g(x)$ is zero for all $x \in \mathbb{R}$.

Thus, $f \cdot g = 0$ in A, and hence A is not a domain.

14.3 Product Rings

Let R_1 and R_2 be rings. Define $R = R_1 \times R_2$ with coordinate-wise addition and multiplication:

$$\begin{aligned} (r_1, r_2) + (r_1', r_2') &:= (r_1 + r_1', r_2 + r_2') \\ (r_1, r_2) \cdot (r_1', r_2') &:= (r_1 \cdot r_1', r_2 \cdot r_2') \\ O_R &:= (O_{R_1}, O_{R_2}) \end{aligned}$$

Then R is not a domain because:

$$(r, 0) \cdot (0, r_2) = (0_{R_1}, 0_{R_2}) = O_R$$

14.4 When is the set of real numbers a domain?

Let $n \in \mathbb{Z}$ with $n \neq 0, \pm 1$.

14.5 Non-prime natural numbers

If n is not prime, then $n = ab$ for some $a, b \neq \pm 1$.

$$[a] \cdot [b] = [ab] = [n] = [0] \text{ in } \mathbb{Z}_n$$

Since $[a]$ and $[b]$ are zero divisors in $\mathbb{Z}_n$, $\mathbb{Z}_n$ is not a domain.

14.6 Prime natural numbers

If n is prime, then $\mathbb{Z}_n$ is a domain:

Suppose $[a] \cdot [b] = [0]$ in $\mathbb{Z}_n$. Then $n \mid ab$.

Since n is prime, $n \mid a$ or $n \mid b$. Thus, $[a] = [0]$ or $[b] = [0]$ in $\mathbb{Z}_n$.

Therefore, $\mathbb{Z}_n$ is a domain.

14.7 Is the set of integers a field when n is prime?

Yes, $\mathbb{Z}_n$ is a field when n is prime.

Let $[a] \in \mathbb{Z}_n$ with $[a] \neq [0]$, i.e., $n \nmid a$.

Then $\gcd(a, n) = 1$. By the Extended Euclidean Algorithm, there exist integers x and y such that:

$$xa + yn = 1$$

Thus,

$$[x] \cdot [a] = [1]$$

So, every non-zero element in $\mathbb{Z}_n$ has a multiplicative inverse, making $\mathbb{Z}_n$ a field.

14.8 Finite Ring as a Field

Proposition 67

Let D be a ring with 1. If D is finite, then D is a field.

Proof. Let $a \in D$ with $a \neq 0$. Consider the mapping:

$$\lambda_a : D \to D$$

$$x \mapsto a \cdot x$$

Claim: λ_a is injective.

Suppose $\lambda_a(x) = \lambda_a(y)$ for $x, y \in D$. Then:

$$a \cdot x = a \cdot y$$

$$a \cdot (x - y) = 0$$

Since D is a domain and $a \neq 0$, it follows that $x = y$. Thus, λ_a is injective.

Since D is finite and λ_a is injective, λ_a is also surjective. Hence, λ_a is a bijection. In particular, $\lambda_a(x) = 1$ for some $x \in D$, i.e., $a \cdot x = 1$.

Thus, every non-zero element in D is invertible, making D a field. □

15 February 14, 2025

Definition 68 (Commutative Ring)
Let R be a commutative ring with 1. An ideal $I \subset R$ is a subset satisfying the following properties:

1. $I \neq \emptyset$
2. I is closed under subtraction, i.e., for all $i, j \in I$, $i - j \in I$.
3. I is closed under multiplication by R, i.e., for all $i \in I$ and $r \in R$, $r \cdot i \in I$.

Here, (2) and (3) imply that:

- $0 \in I$
- $i + j \in I$ for all $i, j \in I$.

Let's take a look at some examples:

1. For $R =$ any commutative ring with 1,
   - R is an ideal of R (often called the unit ideal).
   - $\{0\}$ is an ideal of R, the zero ideal.
2. For any $a \in R$, let
$$(a) = \{a \cdot r : r \in R\}$$
   This is an ideal, called the principal ideal generated by a.
   - $a = a \cdot 1 \in (a)$, so $(a) \neq \emptyset$.
   - Let $i_1 = a \cdot r_1$, $i_2 = a \cdot r_2 \in (a)$. Then $i_1 - i_2 = a \cdot r_1 - a \cdot r_2 = a \cdot (r_1 - r_2) \in (a)$. So (a) is closed under subtraction.
   - Let $i = a \cdot s \in (a)$. Let $r \in R$. Then
$$r \cdot (a \cdot s) = a \cdot (rs) \in (a)$$
     since multiplication in R is commutative and associative. So (a) is closed under multiplication by R.

   It follows that $(a) \subset R$ is an ideal.
3. More generally: Let $S \subset R$ be an arbitrary non-empty subset. Define
$$(S) := \{r_1 \cdot s_1 \cdot \ldots \cdot r_n \cdots s_n : s_1, \ldots, s_n \in S\}$$
   (We often denote this by (S) too.)

   Claim: $(S) \subset R$ is an ideal.

   Proof: Exercise. Very similar to the proof from example (2).

Note: When $S = \{a\}$, $(S) = (a)$. In particular, $(0) = \{0\}$, the zero ideal.

4. $R \simeq \mathcal{H}$:

   Claim: All ideals in $\mathcal{H}$ are principal.

   Proof: Let $I \subset \mathcal{H}$ be an ideal.

   - If $I = (u)$, we are done.
   - If $I \neq (u)$, let $0 \neq a \in I$ be a non-zero element with minimal norm. Let $b \in I$ be any element. By the division algorithm, there is some $k \in \mathcal{H}$ satisfying: $r = b - ka$ and $|r| < |a|$.
     - Since I is closed under subtraction and multiplication by $\mathcal{H}$, $r = b - ka \in I$.
     - Since $|a|$ is minimal among all non-zero elements of I and since $r \in I$ satisfies $|r| < |a|$, it follows that $r = 0$. Thus, $b = k \cdot a \in (a)$.

     Thus, $I \subset (a)$.
     On the other hand, since $a \in I$ and I is closed under multiplication by $\mathcal{H}$, it follows that $(a) \subset I$.
     Thus, $(a) \subset I \subset (a) \Rightarrow I = (a)$ is principal.

   In particular, let $a, b \in \mathbb{Z}$. Since all ideals of $\mathbb{Z}$ are principal, the ideal

   $$(a, b) = \{xa + yb : x, y \in \mathbb{Z}\}$$

   must equal (d) for some $d \in \mathbb{Z}$. d is a greatest common divisor of a and b.

   The Extended Euclidean Algorithm finds the generator for (a, b) explicitly.

   Exercise: For integers $a_1, \ldots, a_n \in \mathbb{Z}$, explain how to use the Extended Euclidean Algorithm to explicitly find $d \in \mathbb{Z}$ for which $(a_1, \ldots, a_n) = (d)$.

15.1 Multivariate Polynomial Rings

Let R be a commutative ring with 1.

Definition 69

$$R[x_1, \ldots, x_n] := \left\{ \text{formal expressions } \sum_{\bar{I} \in \mathbb{N}^n} c_{\bar{I}} x^{\bar{I}} : c_{\bar{I}} \in R \text{ for all } \bar{I}, c_{\bar{I}} \neq 0 \text{ for all but finitely many } \bar{I} \in \mathbb{N}^n \right\}$$

For $\bar{I} = (i_1, \ldots, i_n) \subset \mathbb{N}^n$, $x^{\bar{I}}$ is the monomial

$$x_1^{i_1} \ldots x_n^{i_n}$$

Define addition and multiplication by:

- Addition:

$$\sum_{\bar{I}} c_{\bar{I}} x^{\bar{I}} + \sum_{\bar{I}} c'_{\bar{I}} x^{\bar{I}} := \sum_{\bar{I}} (c_{\bar{I}} + c'_{\bar{I}}) \cdot x^{\bar{I}}$$

- Multiplication:

$$\left(\sum_{\bar{I}} c_{\bar{I}} x^{\bar{I}}\right)\left(\sum_{\bar{J}} d_{\bar{J}} x^{\bar{J}}\right) := \sum_{\bar{K}}\left(\sum_{\bar{I}+\bar{J}=\bar{K}} c_{\bar{I}} d_{\bar{J}}\right) x^{\bar{K}}$$

Example: In $\mathbb{Z}[x, y]$

$$\left(3x + 4xy + 5y^2\right) + \left(7x^3 + 8xy + 13y^2\right) = 3x + 7x^3 + 12xy + 18y^2$$

$$(3x + 4y) \cdot \left(5xy + 6x^2y^3\right) = 15x^2y + 18x^3y^3 + 20xy^2 + 24x^2y^4$$

16 February 17, 2025

16.1 Polynomial Rings

Recall: (Multivariate) polynomial ring $R[x_1, \ldots, x_n]$

$$R[x_1, \ldots, x_n] := \left\{\sum_I c_I x^I : c_I \in R,\ I \in \mathbb{N}^n \text{ such that } c_I = 0 \text{ for all but finitely many } I\right\}$$

$$(x_1, \ldots, x_n)^{(i,j,\ldots,i,n)}$$

16.2 Addition

$$-\left(\sum_I c_I x^I\right) + \left(\sum_I d_I x^I\right) = \sum_I (c_I + d_I) x^I$$

16.3 Multiplication

$$\left(\sum_I c_I x^I\right) \cdot \left(\sum_I d_I x^I\right) = \sum_k \left(\sum_{I|Ik} c_I d_I\right) x^k$$

16.4 Examples

$$0 : \quad (c_I = 0 \text{ for all } I \in \mathbb{N}^n)$$

$$\frac{1}{1} : \quad \left(c_I = \begin{cases} 0 & \text{if } I \neq (0, \ldots, 0) \\ 1 & \text{if } I = (0, \ldots, 0) \end{cases}\right)$$

16.5 Exercise

$R[x_1, \ldots, x_n]$ is a commutative ring with 1.

Lemma 70
If R is an integral domain, $R(x)$ is an integral domain.

Proof. Suppose $a, b \in R(x)$ with $a, b \neq 0$. Then

$$a = a_0 + \cdots + a_j x^j,\ a_j \neq 0$$
$$b = b_0 + \cdots + b_k x^k,\ b_k \neq 0$$

$$a \cdot b = \cdots + a_j b_k x^{j+k}$$

Since R is a domain and $a_j, b_k \neq 0$, the leading coefficient $a_j b_k$ of $a \cdot b$ is $\neq 0$. Therefore, $a \cdot b \neq 0$. It follows that $R(x)$ is an integral domain.

□

16.6 Corollary

Let R be an integral domain. Then $R(x_1, \ldots, x_n)$ is an integral domain too.

16.6.1 Proof

Since $R(x_1, \ldots, x_n) = (R(x_1, \ldots, x_{n-1}))(x_n)$, this follows from the above Lemma by induction on n.

16.7 Ideals in C[x, y]

16.8 Non-principal ideals

Not all ideals in $\mathbb{C}[x, y]$ are principal!
For example, $\overline{I} = (x, y)$.

16.8.1 Proposition

$(x, y) \in \mathbb{C}[x, y]$ is not a principal ideal.

16.8.2 Proof

Suppose $(x, y) = (p)$ for some $p \in \mathbb{C}[x, y]$. Then $x = \alpha \cdot p$ for some $\alpha, \beta \in \mathbb{C}[x, y]$.

$$y = \beta \cdot p$$

16.8.3 Lemma

For $x = \alpha \cdot p$, either α or p is a (non-zero) constant.

$$p = d_0(y) + d_1(y) \cdot x + \ldots + d_k(y) x^k, \quad d_i \in \mathbb{C}[y]$$

$$\alpha \cdot p = c_0(y)d_0(y) + [c_1(y)d_0(y) + c_0(y)d_1(y)]x + \dots$$

Since $\alpha \cdot p = x$,

$$c_0(y)d_0(y) = 0$$
$$c_1(y)d_0(y) + c_0(y)d_1(y) = 0$$

Since $\mathbb{C}[y]$ is a domain, either $c_0 = 0$ or $d_0 = 0$.
Suppose $c_0 = 0$. Then α is a multiple of x.
Say $\alpha = x \cdot \bar{x}$ for some $\bar{x} \in \mathbb{C}[x, y]$.
Then $x \cdot \bar{x} \cdot p = x$

$$\Rightarrow x(\bar{x} \cdot p - 1) = 0$$
$$\Rightarrow \bar{x} \cdot p - 1 = 0 \, \text{since} \, \mathbb{C}[x, y] \, \text{is a domain}$$
$$\Rightarrow \bar{x} \cdot p = 1$$

But $\mathbb{C}[x, y]^\times$ = non-zero constant polynomials.

16.8.4 Exercise

Prove that $\mathbb{C}[x, y]^\times = \mathbb{C}^\times$.

$$\therefore p = (\text{non-zero constant}) \, \text{and} \, \alpha = x \cdot p$$

16.8.5 Symmetrically

If $d_0 = 0$, then $\alpha = (\text{non-zero constant})$ and $p = x \cdot \alpha$.
- If p = non-zero constant, then

$$(x, y) \neq \mathbb{C}[x, y] = (p), \, \text{e.g.} \, 1 \in \mathbb{C}[x, y] \, \text{but} \, 1 \notin (x, y).$$

- If p is non-zero constant, the above lemma proves that

$$p = \frac{x}{\text{non-zero constant}} \alpha \quad \text{or} \quad p = \frac{y}{\text{non-zero constant}} \beta$$

Cannot both hold simultaneously. It follows that (x, y) is not principal.

16.9 Geometric Perspective on Ideals in C[x, y]

There are natural associations:

$$\text{ideals in} \, \mathbb{C}[x, y] \longleftrightarrow \text{subsets of} \, \mathbb{C}^2$$

$$I \longmapsto V(I) := \{s \in \mathbb{C}^2 : f(s) = 0 \, \text{for all} \, f \in I\}$$

$$\Gamma(S) \longleftrightarrow S$$

$$\Gamma(S) := \{f \in \mathbb{C}[x, y] : f(s) = 0 \text{ for all } s \in S\}$$

Then: (Hilbert's Nullstellensatz)

The above maps V, I induce bijections

$$\begin{array}{c} \text{radical ideals} \\ \subset \mathbb{C}[x, y] \end{array} \longleftrightarrow \begin{array}{c} \text{algebraic subsets} \\ \text{of } \mathbb{C}^2 \end{array}$$

$$I \longmapsto V(I)$$

$$I(S) \longleftrightarrow S$$

16.10 Definition

An ideal $I \subset \mathbb{C}[x, y]$ is radical if

$$I = \bar{I} := \{f \in \mathbb{C}[x, y] : f^n \in \bar{I} \text{ for some integer } n \geq 1\}$$

16.11 Definition

A subset $S \subset \mathbb{C}^2$ is algebraic if it is the common zero set of some collection of polynomials in $\mathbb{C}[x, y]$.

16.12 Note

"Nullstellensatz" is German, translating to "Theorem of zeros" in English. It is a deep and important result, lying at the beginnings of algebraic geometry, a mathematical discipline which brings geometric ideas to bear on algebra and vice versa.

This gives an intuitive perspective on why $(x, y) \subset \mathbb{C}[x, y]$ is not a principal ideal.

- $V((x, y)) = \{0, 0\} \subset \mathbb{C}^2$, a single point. - $V((p)) = \{s \in \mathbb{C}^2 : p(s) = 0\}$.

17 February 19, 2025

17.1 Motivation

The theory of ideals in $\mathbb{Z}$ is straightforward ultimately because of the existence of a division algorithm:

Let $a, b \in \mathbb{Z}$, $a \neq 0$. There exists $k \in \mathbb{Z}$ for which:

$$r = b - k \cdot a \text{ satisfies } |r| < |a|$$

The absolute value function

$$|\cdot| : \mathbb{Z} \longrightarrow \mathbb{N} = \{0, 1, 2, \ldots\}$$

is a useful measure of complexity of integers. Abstractly, any function

$$c : \mathbb{Z} \longrightarrow \mathbb{N}$$

satisfying $c(n) = 0 \Leftrightarrow n = 0$

- For every $a, b \in \mathbb{Z}, a \neq 0$, there is some $k \in \mathbb{Z}$ for which $r = b - k \cdot a$ satisfies:

$$c(r) < c(a)$$

could be used as the basis for a (terminating) division algorithm/Euclidean algorithm.

Polynomial rings $F[x]$ admit such a complexity function which can be used as the basis for a division algorithm/Euclidean algorithm.

Definition: Let $p = c_0 + c_1 x + \cdots + c_d x^d \in F[x]$ with $c_d \neq 0$. The degree of p is defined to be d.

$$\deg(p) := \max\{k : c_k \neq 0\}$$

We define $\deg(0) = -\infty$. Degree is analogous to $\log|\cdot|$:

$$\deg \Longleftrightarrow \log|\cdot|$$

Then, (Division algorithm in $F[x]$) Let $a, b \in F[x]$, the polynomial ring in 1-variable over the field F. Suppose $a \neq 0$. Then there is some $q \in F[x]$ satisfying:

$$\deg(r := b - q \cdot a) \leq \deg(a)$$

Note: In the sense of the above motivation, $2\deg(\cdot)$ is a complexity function for the division algorithm.

19. Suppose the leading coefficient of a equals 1, i.e., a is monic.

If a has leading coefficient $c \neq 0$ missed, replace a by $a' = \frac{a}{c}$. If we find $k \in F[x]$ satisfying

$$\deg(b - k \cdot a') \leq \deg(a') = \deg(a),$$

then

$$\deg(b - (\underbrace{k \cdot c}_{c}) \cdot a) < \deg(a)$$

fulfilling the requirement of the theorem statement.

Suppose also that $\deg(b) \geq \deg(a)$.

$$\begin{cases} \text{If } \deg(b) < \deg(a), \\ b = 0 \cdot a + b \text{ fulfills the division algorithm requirements.} \end{cases}$$

We recursively construct a sequence of polynomials

$$b^{(0)} = b, b^{(1)}, b^{(2)}, \ldots, b^{(n)} =: r$$

restricting the property that

- $b^{(0)} = b$ - $b^{(i+1)} = b^{(i)} - k_i \cdot a$ for some $k_i \in F[x]$ - $\deg(b^{(i+1)}) < \deg(b^{(i)})$ for all i. - $\deg(b^{(n)}) < \deg(a)$.

Then $r = b^{(n)}$

$$\begin{aligned} &= b^{(n-1)} + k_{n-1} \cdot a \\ &= b^{(n-2)} + k_{n-2} \cdot a + k_{n-1} \cdot a \\ &= \vdots \\ &= b^{(0)} + k_1 \cdot a + k_2 \cdot a + \cdots + k_n \cdot a \\ &= b + k \cdot a \end{aligned}$$

where $k = k_1 + k_2 + \cdots + k_n \in F[x]$ and $\deg(r) = \deg(b^{(n)}) \leq \deg(a)$.

Let $a = c_0 + \cdots + c_d x^d$.

$\rightarrow$ Begin with $b^{(0)} = b$.

$\rightarrow$ Given $b^{(i)}$ with $\deg(b^{(i)}) \geq \deg(a)$

- Suppose $b^{(i)} = d_0 + d_1 x + \cdots + d_k x^k$ with $d_k \neq 0$

$$(\text{so } \deg(b) \geq \deg(a) = d)$$

- Let $k_i = d_k x^{k-d}$.

$$b^{(i+1)} = b^{(i)} - k_i \cdot a$$

Note: $k_i \cdot a = d_k x^{k-d}(c_0 + \cdots + c_d x^d)$

$$= \text{lower order} + d_k x^k$$

which has the same leading monomial as $b^{(i)}$. These leading monomials cancel upon taking the difference:

$$\begin{aligned} \deg(b^{(i+1)}) &= \deg(b^{(i)} - k_i \cdot a) \\ &< \deg(b^{(i)}) \end{aligned}$$

- If $\deg(b^{(i+1)}) < \deg(a)$, stop.

Otherwise, continue this procedure.

This procedure must stop at some point, say at $i + 1 = n$, since $\deg(b^{(n)}) > \deg(b^{(n)}) \geq \ldots$ is a strictly decreasing sequence of non-negative integers. $b^{(n)}, b^{(n)}, \ldots, b^{(n)}$ is thus the desired sequence.

Remark: The need to divide by the leading coefficient of a - as the parenthetical remark in the latter paragraph - is the only reason the division algorithm does not apply in $R[x]$ for more general rings R. The latter paragraph does show, however, that for any $b \in R[x]$ and any $a \in R[x]$ whose leading coefficient lies in $R^{\times}$, we can fulfill the statement of the division algorithm, i.e., there exists $q \in R[x]$ for which $r := b - q \cdot a$ satisfies $\deg(r) < \deg(a)$.

17.2 Example

(i) $b = x^3 + 2x^2 + 3x + 4$; $a = x^2 + 5x + 6$; $b^{(0)} = b = x^3 + 2x^2 + 3x + 4$

$$b^{(1)} = b^{(0)} - x \cdot a$$

$$\begin{aligned} &= x^3 + 2x^2 + 3x + 4 \\ &- (x^3 + 5x^2 + 6x) \\ &= -3x^2 - 3x + 4 \end{aligned}$$

$$\begin{aligned} b^{(2)} &= b^{(1)} - (-3) \cdot a \\ &= -3x^2 - 3x + 4 \\ &+ 3(x^2 + 5x + 6) \\ &= 12x + 22 \end{aligned}$$

$\Rightarrow \quad b = (x + (-3)) \cdot a + 12x + 22$

Consistency check:

$b = q \cdot a + 12x + 22$

$\to a$ has roots $-2, -3$.

$$\begin{aligned} \text{RHS}(x)(-2) &= 12(-2) + 22 = -2 \\ \text{LHS}(x)(-3) &= 12(-3) + 22 = -14 \end{aligned}$$

By direct computation:

$$\begin{aligned} \text{LHS}(x)(-2) = b(-2) = (-2)^3 + 2(-2)^2 + 3(-2) + 4 = -2 \\ \text{LHS}(x)(-3) = b(-3) = (-3)^3 + 2(-3)^2 + 3(-3) + 4 = -14 \end{aligned}$$

18 February 21, 2025

19 February 24, 2025