

Lang's Algebra Chapter 3 Solutions

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- (1) By the second isomorphism theorem, we have

$$\frac{U}{U \cap W} \cong \frac{U + W}{W}.$$

For two vector spaces, $X \supseteq Y$ over a field K , we have $\dim X/Y = \dim X - \dim Y$. Thus $\dim U - \dim U \cap W = \dim U + \dim W - \dim W$.

- (2) Let M be a module over a commutative ring R . Let I be a maximal ideal of R . We first show that for any proper ideal \mathfrak{a} of R and basis set $\{x_1, x_2, \dots\}$, of M ,

Lemma 1.

$$\frac{M}{\mathfrak{a}M} \cong \bigoplus_i \frac{A}{\mathfrak{a}}(x_i + \mathfrak{a}x_i).$$

Proof. $\mathfrak{a}M$ is submodule of M because $\mathfrak{a}M \subseteq M$ by R -closure property of \mathfrak{a} . It immediately follows that $\mathfrak{a}M = \bigoplus_i \mathfrak{a}x_i$. By linear independence of x_i , $(\sum_i r_i x_i) \bmod \mathfrak{a}x_j = (r_j \bmod \mathfrak{a})x_j + \sum_{i \neq j} r_i x_i$. Therefore, $M/\mathfrak{a}M = \bigoplus_i A x_i / \mathfrak{a}x_i$. By the isomorphism $x_i \mapsto 1_A \mapsto (x_i + \mathfrak{a}x_i)$, $A x_i / \mathfrak{a}x_i \cong A/\mathfrak{a} \cong A/\mathfrak{a}(x_i + \mathfrak{a}x_i)$. \square

Taking \mathfrak{a} as a maximal ideal of R in the above lemma, we see that $M/\mathfrak{a}M$ is a direct product of vector spaces over the field A/\mathfrak{a} and thus admit a basis of the same cardinality as that of M . Because the dimension of a vector space is independent of the basis choice, M also has a fixed dimension.

- (3) Let $\{x_1, \dots, x_m\}$ form the basis set of R over k and let $1_R = k_1 x_1 + \dots + k_m x_m$ for $k_i \in k$. For any element $\mathfrak{a} \in R$, define the sequences $\{y_1, \dots, y_m\} \subseteq k$, $\{f_1, f_2, \dots, f_m\} \subseteq R$ as:

$$f_1 = \mathfrak{a}, \quad y_1 = w_{1,1}^{-1} k_1$$

$$f_{i+1} = f_i y_i - k_i x_i, \quad y_i = k_i w_{i,i}^{-1},$$

,where $f_i = \sum_j w_{i,j} x_j$. By construction, $\mathfrak{a}^{-1} = \sum_i y_i x_i$. Thus R is a field.

- (4) **Direct Sums**

- (a) First, we show the equivalence of the two statements of the theorem. Suppose there is φ such that $g \circ \varphi = \text{id}$. By the injectiveness of the composition, $\text{Im } \varphi \cap \ker g = \{0\}$. But by exactness, $\ker g = \text{Im } f$. We can unambiguously define $\psi(u)$ to be the inverse image of $f^{-1}(u')$ where $u' \equiv u \bmod \text{Im } \varphi$ and $u' = f(x)$ for some $x \in M'$ because if $f(x) = f(y) \bmod \text{Im } \varphi$, $f(x-y) \in \text{Im } \varphi$ and by injectivity of f , $x = y$. Since $M/\text{Im } f \cong M'' = \text{Im } \varphi$, ψ is defined in all of M . Similarly, if the second statement is true, $\ker \psi \cap \text{Im } f = \{0\}$ because $\psi \circ f$ is injective. By exactness, $\text{Im } f = \ker g$. We can then define $\varphi(u) = u'$ where $u' = y \bmod \ker \psi$ and $g(y) = u$ for some y . φ is well-defined because if $g(y_1) = g(y_2)$ for $y_1 \neq y_2$, then $y_1 \neq y_2 \bmod \ker \varphi$.

Now suppose $x \in M$. $x - \varphi(u) \in \text{Im } f$ for exactly one u by the argument mentioned previously. Thus we can express $x = r + s$ where $r = \varphi(u) \in \text{Im } \varphi$ and $s = x - \varphi(u) \in \text{Im } f$. This implies $M = \text{Im } f \oplus \text{Im } \varphi$. By bijectiveness of $g \circ \varphi$, $\text{Im } \varphi \cong M''$. By contrast, if $M = \text{Im } f \oplus N$ for some N , with isomorphism $t : N \rightarrow M''$. We can define $g : M \rightarrow M''$ as $g(u) = u'$ such that there is $u = y \bmod N$ and $t^{-1}(u') = y$. This definition is unambiguous because $N \cap \text{Im } f = \{0\}$. Since $g \circ t^{-1} = \text{id}$,

the sequence splits.

Finally, we complete the details of proposition 3.2. We have just shown $M = \text{Im } f \circ \text{Im } \varphi$. By exactness, $\text{Im } f = \ker g$. Also, $\text{Im } f \cong M'$ and $\text{Im } \varphi \cong M''$ by injectivness of f and φ resp. This proves $M \cong M' \oplus M''$. We can write $x \in M$ as $f(u) + x - f(u)$ where $x - f(u) \in \ker \psi$. u is then uniquely determined by x as $\ker \psi \cap \text{Im } f = \{0\}$ by bijectivness of $\psi \circ f$. This shows $M = \text{Im } f \oplus \ker \psi$.

- (b) First, we note that φ_i is injective because otherwise the composition $\psi_i \circ \varphi_i$ wouldn't be injective, a contradiction. This implies, for every valid i , there is a submodule $E'_i = \text{Im } \varphi_i$ of E that is isomorphic to E_i . Moreover, if $c \in \text{Im } \varphi_i \cap \text{Im } \varphi_j$ for $i \neq j$, then $\psi_i(c) = \psi_j(c) = 0$, forcing c to be 0. These statements prove

$$\bigoplus_{i=1}^n E'_i \subseteq E.$$

The inverse inclusion follows as follows. Let $x \in E$, then $x = \sum_{i=1}^n \varphi_i(\psi_i(x))$, but $\varphi_i(\psi_i(x)) \in E'_i$. Therefore $x \in \bigoplus_{i=1}^n E'_i$.

Let $x = x_1 + \dots + x_m$ where $x_i \in E'_i$. The map defined by $x \mapsto (\psi x_i)_{1 \leq i \leq m}$ is therefore an isomorphism and the inverse map is given by $(\psi x_i)_i \mapsto \sum_i x_i$.

- (5) Let $v'_m = a_1 v_1 + \dots + a_m v_m$. Since $a_m \neq 0$, v'_m , and by the assumption that $\{v_i\}$ is linearly independent over \mathbb{R} , the set $\{v_1, \dots, v_{m-1}, v'_m\}$ is linearly indepenedent over \mathbb{Z} . We also note that, $v'_m - \sum_{i=1}^{m-1} a_i v_i \in A$, thus we can safely assume $a_1 = \dots = a_{m-1} = 0$.

To show, the set spans A , we consider A/A_0 . Suppose, there is $av_m \in A/A_0$ such that $av_m \neq nv'_m$ for all $n \in \mathbb{Z}$. Let r, s be two integers such that $|ra_m + sa| < a_m$. Since contradicts minimality of a_m , it must be the case that $a_m \mid a$. Therefore $A/A_0 = \mathbb{Z}v'_m$.

- (6) We induct on the size of S .

First assume that $S = \{w\}$. Then $\mathbb{Z}\langle S \rangle = \{n[w] : n \in \mathbb{Z}\}$. If M is a subgroup of $\mathbb{Z}\langle S \rangle$, then $M = \mathbb{Z}\langle a[w] \rangle$ for some $a \in \mathbb{Z}$. Here we pick $y_w = a[w]$ which is G -linear.

For the induction step, suppose the statement is true for S , $0 \leq |S| \leq m-1$. We shall prove the statement is true for S with m elements. Fix on element $w \in S$, and consider projection map $\pi : \mathbb{Z}\langle S \rangle \rightarrow \mathbb{Z}\langle G \cdot w \rangle$. By correspondence, $\pi(M)$ is a subgroup of $\mathbb{Z}\langle G \cdot w \rangle$ with basis $\{\tilde{y}_{gw}\}_{w \in G}$ which satisfy the property for $\sigma \in G$, $\sigma \tilde{y}_{gw} = \tilde{y}_{\sigma gw}$. We then lift the basis of $\mathbb{Z}\langle \pi(M) \rangle$ to $\mathbb{Z}\langle S \rangle$ by picking a representatives $\mathfrak{A} = \{y_w\}$ in M for \tilde{y}_w . The y_w are linearly indepenedent thus form part of the basis for M . Again by hypothesis, $M \cap \mathbb{Z}\langle S - G \cdot w \rangle$ has basis $\mathfrak{B} = \{y_w\}_{w \in S - G \cdot w}$ that satisfy the given property. We finally combine \mathfrak{A} and \mathfrak{B} to get the basis of rank m for M .

- (7) For convenience, we identify the properties of a semi-norm as follows

SN-1 $|v| \geq 0$

SN-2 $|nv| = |n||v|$

SN-3 $|u + v| \leq |u| + |v|$

- (a) Let $a, b \in M_0$. Then by SN-2 and SN-3, $|u - b| \leq |a| + |b| = 0$. By SN-1, we have $|a - b| \geq 0$, this $a - b \in M_0$. By SN-2, $|0| = |2 \cdot 0| = 2|0|$. This implies $0 \in M_0$. Hence M_0 is a subgroup of M .

- (b) If $M_0 \neq \{0\}$, we can make the transformation $x \mapsto x + M_0$ without loss of generality as such map preserves the linear independence of $\{v_i\}$. Thus, we can assume $M_0 = \{0\}$.

Let $N = \langle v_1, \dots, v_r \rangle$. Since M has rank r , the exponent e of M/N is finite and thus eM is a subgroup of N . Moreover, N/eM is torsion group with finite number of elements. Therefore, we can pick the smallest positive integers $n_{i,j}$ such that

$$\sum_{j=1}^i n_{i,j} v_j = dw_i \quad \text{for some } w_i \in M$$

The linear independence follows immediately. Picking $n_{j,k}$ in the range $[0, d-1]$,

$$d|w_i| = |dw_i| \leq \sum_{j=1}^i n_{i,j} |v_j| \leq d \sum_{j=1}^i |v_j|.$$

- (8) (a) SN-1 follows immediately because $\log \geq 0$ for all \mathbb{Z}^+ . Since, $h(x^{-1}) = h(x)$, it suffices to prove SN-2 for $n \geq 0$ in which case $h(x^n) = \log \max(|a^n|, |b^n|) = \log \max(|a|, |b|)^n = n \log \max(|a|, |b|) = nh(x)$. Finally, if $y = c/d$, $h(xy) = h(ac/bd)$. Let $e = \gcd(a, d)$ and $f = \gcd(c, b)$. Then

$$\begin{aligned} h(xy) &= \log \max\left(\left|\frac{ac}{ef}\right|, \left|\frac{bd}{ef}\right|\right) \\ &= \log\left(\frac{1}{|ef|}(\max(|ac|, |bd|))\right) \\ &= \log \max(|ac|, |bd|) - \log |ef| \\ &\leq \log \max(|ac|, |bd|) \\ &\leq \log \max(|a|, |b|) + \log \max(|c|, |d|) \end{aligned}$$

Hence SN-3 is satisfied. $\log \max(|a|, |b|) = 0$ if and only if $|a| = |b| = 1$, which makes the kernel of $\ker h = \{\pm 1\}$.

- (b) For a given rational number $x = a/b$, since there are finitely many prime divisors of p, q such that $p|a$ and $q|b$, M can be generated by the set $\{-1, 1\} \cup \{p, 1/q \in \mathbb{Q}^* : p|\text{the numerator of } x_1 \cdots x_m, q|\text{the denominator of } x_1 \cdots x_m\}$. From this we can set upper bound on the norm as

$$h(y) \leq \sum_p \log p$$

where the sum is over all primes p (not necessarily distinct) that divides the numerator or denominator of x_i for some i .

- (9) (a) $S^{-1}M$ can be defined as a subset of $M \times S$ for a commutative ring A , a multiplicative subset S and A -module M such that

$$(m_1, s_1) \sim (m_2, s_2)$$

, if there is an element $s \in S$ that satisfy the equation $s(s_2 m_1 - s_1 m_2) = 0$. As with $S^{-1}A$, we can denote (m, s) with m/s . Since $S^{-1}A$ is a commutative ring, we can define the action of $S^{-1}A$ on $S^{-1}M$ as

$$\frac{a}{s'} \cdot \frac{m}{s} = \frac{a \cdot m}{s' s}.$$

With this definition of the action of $S^{-1}A$ on $S^{-1}M$, we can show that $S^{-1}M$ is an $S^{-1}A$ -module. Let $a_1/b_1, a_2/b_2 \in S^{-1}A$ and let $m_1/s_1, m_2/s_2 \in S^{-1}M$. Then we have

$$\begin{aligned} \frac{a_1}{b_1} \cdot \left(\frac{m_1}{s_1} + \frac{m_2}{s_2} \right) &= \frac{a_1}{b_1} \cdot \left(\frac{m_1 s_2 + m_2 s_1}{s_1 s_2} \right) \\ &= \frac{a_1 b_1}{b_1 b_1} \cdot \left(\frac{m_1 s_2 + m_2 s_1}{s_1 s_2} \right) \\ &= \frac{a_1 b_1 s_2 m_1 + a_1 b_1 s_1 m_2}{b_1 s_1 b_1 s_2} \\ &= \frac{a_1 m_1}{b_1 s_1} + \frac{a_1 m_2}{b_1 s_2} \\ &= \frac{a_1}{b_1} \cdot \frac{m_1}{s_1} + \frac{a_1}{b_1} \cdot \frac{m_2}{s_2}. \end{aligned}$$

and

$$\begin{aligned}
\left(\frac{a_1}{b_1} + \frac{a_2}{b_2}\right) \cdot \frac{m_1}{s_1} &= \left(\frac{a_1 b_2 + a_2 b_1}{b_1 b_2}\right) \cdot \frac{m_1}{s_1} \\
&= \left(\frac{a_1 b_2 + a_2 b_1}{a_1 a_2}\right) \cdot \frac{m_1 s_1}{s_1 s_1} \\
&= \frac{a_1 b_2 m_1 s_1 + a_2 b_1 m_1 s_1}{s_1 b_1 s_2 b_2} \\
&= \frac{a_1 m_1}{b_1 s_1} + \frac{a_2 m_1}{b_2 s_1} \\
&= \frac{a_1}{b_1} \cdot \frac{m_1}{s_1} + \frac{a_2}{b_2} \cdot \frac{m_1}{s_1}.
\end{aligned}$$

(b) Let

$$0 \rightarrow M' \xrightarrow{f} M \xrightarrow{f''} M'' \rightarrow 0$$

be exact. Then we have the induced sequence,

$$0 \rightarrow S^{-1}M' \xrightarrow{g} S^{-1}M \xrightarrow{g''} S^{-1}M'' \rightarrow 0,$$

where g is defined as $g(m/s) = f(m)/s$ and g'' is defined as $g''(m/s) = f''(m)/s$. $\ker g = \{m/s : f(m)/s = 0\}$. Since f is injective, $f(m) = 0$ iff $m = 0$, i.e., $\ker g = \{0\}$.

By exactness $\text{Im } f = \ker f''$. Evaluating g'' on $\text{Im } g$, $g''(g(m/s)) = g''(f(m)/s) = f''(f(m))/s = 0/s = 0$. This shows $\text{Im } g \subseteq \ker g''$. Let $g''(x/s) = f''(x)/s = 0$. This implies $f''(x) = 0$ for some x . By exactness, $\ker f \subseteq \text{Im } f''$, implying $x = f(y)$ for some $y \in M'$. This proves $\text{Im } g \supseteq \ker g''$.

Finally, let $x/s \in S^{-1}M''$. Since $x \in M''$, $x = f''(y)$ for some $y \in M$ by exactness of the first sequence. But then $x/s = f''(y)/s = g''(y/s)$ making g'' surjective.

(10) (a) The natural map under consideration is the map

$$f = x \mapsto (x/1, \dots).$$

If $x/s' \sim 0/1$, for some $s' \in A - \mathfrak{p}$ and $x \in M$, then it means $s'x = 0$ for some $s' \in A - \mathfrak{p}$. Therefore, the kernel of f is the set $\{x : sx = 0, \text{ for some } s \in A - \mathfrak{p} \text{ for all maximal ideals } \mathfrak{p}\}$. If $x \in \ker f$, then $\text{Ann}(x)$ is not contained in any maximal ideal \mathfrak{p} , implying $\text{Ann}(x) = A \implies x = 0$.

(b) Let $f : M' \rightarrow M$ and $\hat{f} : M'_p \rightarrow M_p$. Define g and \hat{g} similarly for the second halves of the sequences.

(\implies) This directly follows from part (b) of exercise 9.

(\impliedby) Suppose $0 \rightarrow M'_p \rightarrow M_p \rightarrow M''_p$ is exact sequence for all primes \mathfrak{p} .

Let $f(x) = 0$, then $\hat{f}(x/s) = f(x)/s = 0/1$ for all $s \in \mathfrak{p}$. By exactness, \hat{f} is injective. thus $x/s = 0$. By similar reasoning as part (a) of this problem $x = 0$. Hence f is injective.

Now let $gf(x) = n$. By definition, $\hat{g}\hat{f}(x/s) = n/s$. By exactness, the left-hand side is 0. Thus $s'n = 0$ for $s' \in \mathfrak{p}$ for all prime \mathfrak{p} . Again, by similar reasoning as part (a), n has to be 0 and $\text{Im } f \subseteq \ker g$. To see the converse, suppose $g(y) = 0$. Consequently, $\hat{g}(y/s) = g(y)/s = 0$ for all $s \in \mathfrak{p}$ and by exactness, $y/1 = \hat{f}(x/t_p) = f(x)/t_p$ for some t_p depending on \mathfrak{p} . This implies $s_p(f(x) - t_p y) = 0$ or equivalently $f(s_p x) = r_p y$ for some $x \in M'_p$ and $r_p = s_p t_p$ implying $r_p y \in \text{Im } f$ for all prime \mathfrak{p} . Since $M/\text{Im } f$ is also an A -module, it implies $r_p(x + \text{Im } f) = 0$ for all \mathfrak{p} implying $x + \text{Im } f = 0 + \text{Im } f$ or in other words, $x \in \text{Im } f$. This proves $\text{Im } f = \ker g$.

Finally, suppose $y \in M''$. By surjectivity of \hat{g} , $y/1 = \hat{g}(x/s) = g(x)/s$ for some $x \in M$. By definition, $s_p(g(x) - t_p y) = 0$. By similar argument as above, $y \in \text{Im } g$, proving the exactness of the first sequence.

(c) Let $\phi : M \rightarrow M_p$ be the natural map in question. Then $\phi(x) = x/1$. If $\phi(x) = 0$, then $sx = 0$ for some $s \in A - \mathfrak{p}$. This contradicts the assumption M is torsion-free and since $0 \notin A - \mathfrak{p}$, $x = 0$.

Projective modules over Dedekind rings

- (11) Let \mathfrak{o} be a Dedekind domain, and let M be a finitely generated torsion-free \mathfrak{o} -module. For each prime ideal \mathfrak{p} , consider the localization $\mathfrak{o}_{\mathfrak{p}}$ and the localized module $M_{\mathfrak{p}}$.

Since $\mathfrak{o}_{\mathfrak{p}}$ is a Dedekind domain with only one prime ideal $S^{-1}\mathfrak{p}$, by the result from the previous chapter it is a PID. Finite generation and torsion-freeness of $M_{\mathfrak{p}}$ follow from the corresponding properties of M , and Theorem 7.3 then implies that $M_{\mathfrak{p}}$ is a free $\mathfrak{o}_{\mathfrak{p}}$ -module (and hence projective).

Now let F be a free \mathfrak{o} -module, and suppose there is a surjective homomorphism

$$f : F \twoheadrightarrow M.$$

Localizing at \mathfrak{p} , we obtain a surjective map

$$f_{\mathfrak{p}} : F_{\mathfrak{p}} \twoheadrightarrow M_{\mathfrak{p}}.$$

Since $M_{\mathfrak{p}}$ is projective, there exists a homomorphism

$$g_{\mathfrak{p}} : M_{\mathfrak{p}} \rightarrow F_{\mathfrak{p}}$$

such that

$$f_{\mathfrak{p}} \circ g_{\mathfrak{p}} = \text{id}_{M_{\mathfrak{p}}}.$$

Because M is finitely generated, say by m_1, \dots, m_r , each $g_{\mathfrak{p}}(m_i/1) \in F_{\mathfrak{p}}$ can be written with a denominator not in \mathfrak{p} . Let $c_{\mathfrak{p}} \in \mathfrak{o} \setminus \mathfrak{p}$ be the product of all these denominators for $i = 1, \dots, r$. Then

$$c_{\mathfrak{p}} g_{\mathfrak{p}}(l_{\mathfrak{p}}(M)) \subseteq F,$$

where $l_{\mathfrak{p}} : M \rightarrow M_{\mathfrak{p}}$ is the localization map.

We claim that the set $\{c_{\mathfrak{p}} : \mathfrak{p} \text{ prime}\}$ generates the unit ideal (1). Indeed, if this ideal were proper, it would be contained in some maximal ideal \mathfrak{m} ; but then $c_{\mathfrak{m}} \in \mathfrak{m}$, contradicting $c_{\mathfrak{m}} \notin \mathfrak{m}$. Thus there exist primes $\mathfrak{p}_1, \dots, \mathfrak{p}_n$ and elements $x_1, \dots, x_n \in \mathfrak{o}$ such that

$$\sum_{i=1}^n x_i c_{\mathfrak{p}_i} = 1.$$

Define

$$g := \sum_{i=1}^n x_i c_{\mathfrak{p}_i} \cdot g_{\mathfrak{p}_i} \circ l_{\mathfrak{p}_i} : M \rightarrow F.$$

This is well-defined since each $c_{\mathfrak{p}_i} g_{\mathfrak{p}_i}(l_{\mathfrak{p}_i}(M)) \subseteq F$.

For $m \in M$, we have

$$f(g(m)) = \sum_{i=1}^n x_i c_{\mathfrak{p}_i} f(g_{\mathfrak{p}_i}(m/1)) = \sum_{i=1}^n x_i c_{\mathfrak{p}_i} (m/1) = \left(\sum_{i=1}^n x_i c_{\mathfrak{p}_i} \right) m = 1 \cdot m = m.$$

Thus $f \circ g = \text{id}_M$, showing that M is a direct summand of F and hence projective.

- (12) (a) Define a map $\mathfrak{a} \oplus \mathfrak{b} \rightarrow \mathfrak{o}$ as

$$(a, b) \mapsto ca + b,$$

where c is as defined in question 19 of chapter II. Since ca and b are coprime the image of this map is \mathfrak{o} . The kernel of this map which is given by $ca \cap \mathfrak{b} \supseteq ca\mathfrak{b}$ also satisfies the reverse inclusion because for $d \in ca \cap \mathfrak{b}$, we can write $d = d(ca + b) = ca \cdot d + d \cdot a \in ca\mathfrak{b}$. Therefore, kernel is $ca\mathfrak{b}$. Since the map $a\mathfrak{b} \rightarrow ca\mathfrak{b}$ is bijective, and \mathfrak{o} is finitely generated and torsion-free (thus free), it follows that

$$\mathfrak{a} \oplus \mathfrak{b} \cong \mathfrak{o} \oplus a\mathfrak{b}$$

- (b) First we show that $f = m_c$ for some $c \in K$. Let $a_1, a_2 \in \mathfrak{a}$. For fixed elements, a_1, a_2 , we can assume $f(a_1) = c_1 a_1$ and $f(a_2) = c_2 a_2$ for $c_1, c_2 \in K$ since both \mathfrak{a} and \mathfrak{b} are contained in the field K . By the definition of fractional ideals, there is an element $c \in \mathfrak{o}$ such that $ca_1, ca_2 \in \mathfrak{o}$ and $ca_1 a_2 \in \mathfrak{a}$. By the \mathfrak{o} -linearity f and by commutativity of K , $f(ca_1 a_2) = ca_1 f(a_2) = ca_2 f(a_1) \implies c_1 = c_2$. Thus $f = m_c$. This also proves $\mathfrak{b} = ca$ for some $c \in K$.

We can define an extension of f , f_K , in K as $f_K(x) = f_K(a^{-1}ax) = a^{-1}xf_K(a) = a^{-1}f(a)x = cx$. f_K is clearly K -linear and agrees with f on \mathfrak{a} .

Remark 2. Lang takes for granted that the assumption that there exists a K -linear map f_K . This is not obvious and we have just proved that in fact there exists a K -linear map that is an extension of f .

- (c) The assertion that m_b is an element of \mathfrak{a}^\vee follows directly from the inclusion $b\mathfrak{a} \subseteq \mathfrak{a}^{-1}\mathfrak{a} = \mathfrak{o}$. This implies $\mathfrak{a}^{-1} \subseteq \mathfrak{a}^\vee$. We show the reverse inclusion holds.

Let $\phi \in \mathfrak{a}^\vee$. By the previous subproblem, it suffices to show that $\phi(\mathfrak{a})$ is an ideal of \mathfrak{o} . Since $\phi(\mathfrak{a})$ is a \mathfrak{o} -submodule of \mathfrak{o} , $\phi(\mathfrak{a})$ is an additive subgroup of \mathfrak{o} . For $a, b \in \mathfrak{a}$, by properties of \mathfrak{o} -homomorphism ϕ , $\phi(\phi(\mathfrak{a})b) = \phi(\mathfrak{a})\phi(b) \in \phi(\mathfrak{a})$. Finally, for $c \in \mathfrak{o}$, $c\phi(\mathfrak{a}) = \phi(c\mathfrak{a}) \subseteq \phi(\mathfrak{a})$ where the last inclusion followed from the definition of fractional ideals.

Thus, we have $\phi(\mathfrak{a}) = c\mathfrak{a}$ where $c = \phi_K(1)$. c has to be a member of \mathfrak{a}^{-1} because otherwise $c\mathfrak{o} + \mathfrak{a}^{-1}$ would be an inverse of \mathfrak{a} making \mathfrak{a}^{-1} non-unique, a contradiction in Dedekind domains.

- (13) (a) M should be torsion-free. Otherwise, by projectivity of M , for some free module $F \supseteq M$ and any surjective \mathfrak{o} -homomorphism $f : F \rightarrow M$, there is a corresponding $g : M \rightarrow F$ such that $f \circ g = \text{id}_M$. If non-zero $x \in M$ is a torsion element, say with exponent $\mathfrak{a} \in \mathfrak{o}$, then $0 = g(ax) = ag(x) \in F$ implying either $a = 0$ or $g(x) = 0$. Since $f(g(x)) = x \neq 0$, it follows $a = 0$, proving M is torsion free.

Localizing M at any prime ideal \mathfrak{p} of \mathfrak{o} , we see that the module $M_{\mathfrak{p}}$ is a PID that is torsion-free and finitely generated. This makes $M_{\mathfrak{p}}$ free. Let $M_{\mathfrak{p}} = \bigoplus_{i=1}^n \mathfrak{o}_{\mathfrak{p}} m_i$. By finiteness of m_i , there is an element $c \in \mathfrak{o}$ such that $cm_i \in M$ for all i . We then find F' as

$$F' = \bigoplus_{i=1}^n \mathfrak{o}(cm_i) \subseteq M.$$

Now, let $\{v_1, \dots, v_k\}$ be the generators of M and let

$$v_i = \sum_{j=1}^n r_j^{(i)} m_i.$$

Pick $d \in \mathfrak{o}$ such that $dr_j^{(i)} \in \mathfrak{o}$ which exists by the finiteness of $r_j^{(i)}$. It follows that $dM \subseteq \bigoplus_{i=1}^n \mathfrak{o}m_i$ and that

$$M \subseteq \bigoplus_{i=1}^n \mathfrak{o}\left(\frac{1}{d}m_i\right) = F.$$

The equality $\text{rank } F = \text{rank } F'$ immediately follows.

- (b) Let $\frac{1}{d}m_i = e_i$ in the proof of (b). We prove the statement by inducting on the number of basis elements, n .

When $n = 1$, then define $\mathfrak{a}_1 = \{a : ae_1 \in M\}$. This subset of \mathfrak{o} is an ideal of \mathfrak{o} because if $m = ae_1$ for some a , then $rae_1 = rm \in M$ for any $r \in \mathfrak{o}$.

For the induction step, suppose N is a submodule of M spanned by e_1, \dots, e_{n-1} . By induction hypothesis, $N = \bigoplus_{i=1}^{n-1} \mathfrak{a}_i e_i$. Consider the exact sequence

$$0 \rightarrow N \rightarrow M \rightarrow M/N \rightarrow 0.$$

Since $\text{rank } M/N = \text{rank } M - \text{rank } N = 1$, and by the projectivity of M/N , the induction follows.

- (c) The statement that $M \cong \mathfrak{o}^{n-1} \oplus \mathfrak{a}$ for some ideal \mathfrak{a} follows immediately from part (b) of this problem and part (a) of problem 12.

Let $F : K_0(\mathfrak{o}) \rightarrow \text{Pic}(\mathfrak{o})$ be the given association. First, we show that this association is a group homomorphism. By the linear independence of F (as defined in (a)), the 'decomposition' of M in terms of \mathfrak{a}_i is unique. Thus, $\mathfrak{a} = \mathfrak{a}_1 \cdots \mathfrak{a}_n$ is uniquely determined by M , making F a well-defined mapping. Consider M, N are two finite projective modules. Then $F(M) + F(N) = \mathfrak{o}^{n-1} \oplus \mathfrak{a} \oplus \mathfrak{o}^{m-1} \oplus \mathfrak{b} = \mathfrak{o}^{n+m-2} \oplus \mathfrak{a} \oplus \mathfrak{b} = \mathfrak{o}^{n+m-1} \oplus \mathfrak{ab} = F(M \oplus N)$. Thus F is a group homomorphism.

Let $M \in \ker F$. Then, $F(M) = \mathfrak{o}$. This implies $M = \mathfrak{o}^n$ is free which is a single equivalence class in $K_0(A)$. Therefore, $M = [0]$. Finally, taking M as any ideal \mathfrak{a} of \mathfrak{o} as \mathfrak{o} -module, we see that $F(M) = \mathfrak{a}$, making F surjective and thus an isomorphism.

A few snakes

(14) Let $M' \xrightarrow{\phi'} M \xrightarrow{\phi} M'' \rightarrow 0$ and let $0 \rightarrow N' \xrightarrow{\psi'} N \xrightarrow{\psi} N''$ be the two exact sequence in the diagram.

(a) Let $g(x) = 0$. By commutativity, $\psi(gx) = h(\phi x) = 0$. By the injectivity of h , $\phi(x) = 0$. By exactness of the top sequence, $x = \phi'(y)$ for $y \in M'$. By commutativity of the diagram, $0 = g(\phi'y) = \psi'(fy)$. By exactness of the bottom sequence $f(y) = 0$. By the injectivity of f , then $y = 0$ and its image under ψ' , x is also 0. This proves g is a mono-morphism.

(b) Let $x \in N$. Then $\psi x \in N''$. By surjectivity of h and ϕ , there is an element $y \in M$ such that $h(\phi y) = \psi x$. By commutativity, it follows that $\psi x = \psi(gy)$ and consequently $x - gy \in \ker \psi$. By exactness, $x - gy = \psi'z$ for some $z \in N'$ and by surjectivity of f , $x - gy = \psi'(fw)$ for some $w \in M'$. By commutativity, it follows that $x - gy = g(\phi'w)$ or $x = g(y + \phi'w)$, implying $x \in \text{Im } g$ (g is surjective).

(c) If f and h are isomorphisms, then g is isomorphisms by (a) and (b) of this problem.

Consider g and h are isomorphisms, i.e., $\ker g = \ker h = \text{Coker } g = \text{Coker } h = 0$. By the snake lemma, there is a map $\ker h \rightarrow \text{Coker } f$ showing f is surjective. By injectivity of the map $M' \rightarrow M$, $\ker f \rightarrow \ker g$ is injective, making $\ker f = 0$. Hence, f is an isomorphism.

Now suppose f and g are isomorphisms. By the snake lemma, $\ker g \rightarrow \ker h \rightarrow \text{Coker } f$ is exact. Since $\ker g = \text{Coker } f = 0$, $\ker h = 0$. Similarly, by the exactness of the sequence $\text{Coker } g \rightarrow \text{Coker } h \rightarrow 0$, $\text{Coker } h = 0$.

(15) We denote the module homomorphisms as follows:

$$\begin{array}{ccccccccc} M_1 & \xrightarrow{\alpha} & M_2 & \xrightarrow{\beta} & M_3 & \xrightarrow{\gamma} & M_4 & \xrightarrow{\delta} & M_5 \\ \downarrow f_1 & & \downarrow f_2 & & \downarrow f_3 & & \downarrow f_4 & & \downarrow f_5 \\ N_1 & \xrightarrow{\alpha'} & N_2 & \xrightarrow{\beta'} & N_3 & \xrightarrow{\gamma'} & N_4 & \xrightarrow{\delta'} & N_5 \end{array}$$

We apply the snake lemma on the following diagram:

$$\begin{array}{ccccccccc} 0 & \longrightarrow & \beta M_2 & \longrightarrow & M_3 & \longrightarrow & \gamma M_3 & \longrightarrow & 0 \\ & & \downarrow f_3|_{\beta M_2} & & \downarrow f_3 & & \downarrow f_4|_{\gamma M_3} & & \\ 0 & \longrightarrow & \beta' N_2 & \longrightarrow & N_3 & \longrightarrow & \gamma' N_3 & \longrightarrow & 0 \end{array}$$

Exactness of the top and bottom sequence and commutativity of the diagram follow immediately. By the snake lemma, we have the short exact sequence:

$$0 \rightarrow \ker f_3|_{\beta M_2} \rightarrow \ker f_3 \rightarrow \ker f_4|_{\gamma M_3} \rightarrow \text{Coker } f_3|_{\beta M_2} \rightarrow \text{Coker } f_3 \rightarrow \text{Coker } f_4|_{\gamma M_3} \rightarrow 0$$

(a) By assumption $\ker f_4|_{\gamma M_3} = 0$. Thus, it suffices to show that $\ker f_3|_{\beta M_2} = 0$.

Let $x \in \ker f_3|_{\beta M_2}$. Then $x = \beta(y)$ for some $y \in M_2$. By commutativity, we have $0 = f_3(\beta y) = \beta'(f_2 y)$, implying $f_2 y \in \ker \beta' = \alpha' N_1$ where the last equality follows from the exactness of the bottom sequence. Since f_1 is surjective, there is an element $z \in M_1$ such that $\alpha'(f_1 z) = f_2(\alpha z) = f_2 y$. By injectivity of f_2 , $y = \alpha(z) \implies x = \beta(\alpha z) = 0$. Hence f_3 is injective.

(b) Let $x = \beta'(y) \in \beta' N_2$. By surjectivity of f_2 , $y = f_2(z)$ for some $z \in M_2$. By commutativity, $\beta'(y) = f_3(\beta z) \in f_3 \beta M_2 \implies \text{Coker } f_3|_{\beta M_2} = 0$. Hence, it suffices to prove that $\text{Coker } f_4|_{\gamma M_3} = 0$. Now let $x = \gamma'(y)$ for some $y \in N_3$. By exactness $x \in \ker \delta'$. By surjectivity of f_4 , there is $f_4(z) = x$ and by commutativity $0 = \delta'(f_4 z) = f_5(\delta z)$. Since f_5 is injective, $\delta z = 0 \implies z \in \ker \delta = \gamma M_3$ where the last equality followed from the exactness of the top sequence. Hence $x \in f_4|_{\gamma M_3}$ and $\text{Coker } f_4|_{\gamma M_3} = 0$. This proves the statement.

Remark 3. The diagram-chasing argument is more direct and arguably a better proof. I provided this proof as a practice on the application of the snake lemma.

Inverse limits

(16) Let I be a directed set and let $\{A_i\}_{i \in I}$ be a system of simple groups with surjective homomorphisms $f_{ij} : A_i \rightarrow A_j$ for every $j \leq i$. By the first isomorphism theorem we have $A_j = A_i/N$ for some normal subgroup N of A_i . By simplicity of each A_i , it follows that either $A_i = 0$ or $A_i = A_j$ for all $j \leq i$ (or both). There are two types of such families of groups that could arise:

Case 1 : All $A_i = 0$. In this case, $\varprojlim A_i = 0$.

Case 2 : $A_i = 0$ for all $i < n$ and $A_i = A$ for all $n \leq i$ for some $n \in I$. In this case f_{ij} is an isomorphism for $j \geq n$ and the elements of $\varprojlim A_i$ have the form $(0, \dots, 0, x_n, f_{n+1,n}^{-1}x_n, \dots) \sim x_n \in A$. In other words, $\varprojlim A_i \cong A$ which is simple.

- (17) (a) The set of positive integers is inherently directed by $<$. We define $f_{ij} = \pi_{ij} : A_i \rightarrow A_j$ by $\pi([x]_{p^i}) = [x]_{p^j}$. Let $k \geq j \geq i \in \mathbb{Z}^+$. Then we have $\pi_{ij} \circ \pi_{kj}(x) = [[x]_{p^j}]_{p^i} = [x]_{p^i} = \pi_{ki}(x)$ and trivially $\pi_{ii} = \text{id}$. Hence, $\mathbb{Z}/p^n\mathbb{Z}$ form a projective system under (π_{ij}) .

Let $\mathbb{Z}_p = \varprojlim \mathbb{Z}/p^i\mathbb{Z}$ along with the morphisms $\psi_i : \mathbb{Z}_p \rightarrow \mathbb{Z}/p^i\mathbb{Z}$. Consider the projection maps $\mu_i : \mathbb{Z} \rightarrow \mathbb{Z}/p^i\mathbb{Z}$. Then $\pi_{ij} \circ \mu_i(x) = \pi_{ij}([x]_{p^i}) = [x]_{p^j} = \mu_j(x)$. By universality of \mathbb{Z}_p , there is a unique morphism ϕ from $\mathbb{Z} \rightarrow \mathbb{Z}_p$ such that $\psi_i \circ \phi = \mu_i$. By definition, μ_i are surjective. Hence ψ_i is surjective.

We use induction to show that \mathbb{Z}_p has no divisors of 0. Let $(x_1, x_2, \dots), (y_1, y_2, \dots)$ are non zero elements of \mathbb{Z}_p such that their product is 0. This implies

$$x_i y_i = 0 \pmod{p^i} \text{ for all } i.$$

For $i = 1$, then by the field properties of $\mathbb{Z}/p\mathbb{Z}$, either $x_1 = 0$ or $y_1 = 0$. With out loss of generality, let $x_1 = 0$.

Now suppose $x_i = 0 \pmod{p^i}$ for all $i \leq n-1$ and $x_n \neq 0 \pmod{p^n}$. Since $x_n y_n = 0 \pmod{p^n}$ and $x_{n-1} = 0 \pmod{p^{n-1}}$, $x_n = r_1 p^{n-1} \pmod{p^n}$ for some r_1 not divisible by p . On the other hand, $y_i = s_1 p \pmod{p^n}$ for $s_1 \neq 0 \pmod{p^{n-1}}$ otherwise all $y_i = 0 \pmod{p^i}$ for all $i \leq n$ and the induction step is fulfilled. Similarly, we can deduce that

$$x_{2n-1} = r_1 p^{n-1} + \dots + r_n p^{2n-1} \pmod{p^{2n-2}} \quad \text{and} \quad y_{2n-1} = s_1 p + s_2 p^n + \dots + s_n p^{2n-2} \pmod{p^{2n-1}}$$

Note tha we didn't assume $r_i, s_i \neq 0$ for $i \geq 2$. The product $x_{2n-2} y_{2n-2}$ reduces to $r_1 s_1 p^n \pmod{p^{2n-1}}$. Since $x_{2n-1} y_{2n-1} = 0 \pmod{p^{2n-1}}$, and $p \nmid r_1$ by assumptions $p^{n-1} \mid s_1$ and $y = 0 \pmod{p^n}$ a contradiction. Thus $p \mid r_1$ and $x_n = 0 \pmod{p^n}$.

Since $x_i = 0$ for all i by induction, it implies $(x_1, x_2, \dots) = 0$ and \mathbb{Z}_p has no zero divisors itself.

Next we show that \mathbb{Z}_p has a unique maxmial ideal generated by $p = (0, p, p, \dots)$. To show that the ideal \mathfrak{a} generated by p is maximal consider the quotient group $\mathbb{Z}_p/\mathfrak{a}$. Since $\mathbb{Z}/p^i\mathbb{Z}/(0, p, \dots)\mathbb{Z}_p \cong \mathbb{Z}/p\mathbb{Z}$, the quotien group $\mathbb{Z}_p/\mathfrak{a}$ is (isomorphic to) a subgroup of $\mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/p\mathbb{Z} \dots$ that satisfies the projective system of morphisms $\pi'_{ij} = \text{id}$. Therefore, by surjectivity of ψ_i , $\mathbb{Z}_p/\mathfrak{a}$ is isomorphic to \mathbb{F}_p which is a field and thus \mathfrak{a} is maximal.

To see that \mathfrak{a} is unique, note that if $(x_1, x_2, \dots) \in \mathfrak{b}$ for some proper ideal \mathfrak{b} of \mathbb{Z}_p and if $x_1 \neq 0$, then $x = (x_1, x_2, \dots)$ is a unit whose inverse is $(x_1^{p-2}, x_2^{p^2-p-1}, \dots)$. Therefore, any proper ideal of \mathbb{Z}_p should have its first component of its elements equal to 0. This implies $x_i = px$ for all $i \geq 2$ which implies $\mathfrak{b} = 0 \pmod{\mathfrak{a}}$ implying \mathfrak{a} is unique.

Finally, to see that \mathbb{Z}_p is a factorial ring, we show that it is a PID. Let \mathfrak{b} be an ideal of \mathbb{Z}_p . Then every component of \mathfrak{b} must be an ideal in its domain. But ideals in $\mathbb{Z}/p^n\mathbb{Z}$ are PIDs say with generators y_n (resp.). Then \mathfrak{b} is generated by (y_1, y_2, \dots) . p is the only prime of \mathbb{Z}_p because otherwise an ideal generated by another prime in PID is maximal which contradicts the uniqueness of $p\mathbb{Z}_p$.

- (b) By the chinese remainder theorem, there is a homomorphism $k : \prod_p \mathbb{Z}_p \rightarrow \varprojlim \mathbb{Z}/a\mathbb{Z}$ such that a -th component of $y = k(x)$ is the solutions for equation $y_a = x_n \pmod{p^n}$ for all $p^n \mid a$ and $p^{n+1} \nmid a$, $n \geq 1$. $y = 0$ iff $y_p = 0 \pmod{p}$ for all p which is impossible. Hence k is injective. By the uniqueness of the solution y_a given the projective system, k is also surjective. Hence k is an isomorphism.

- (18) (a) Trivially, we define the action of $\varprojlim A_i$ on $\varprojlim M_i$ as the component-wise action of A_i on M_i . This action is well-defined by the commutivity of the diagram. The module properties $\varprojlim M_i$ as a $\varprojlim A_i$ -module follow directly from the module properties of M_i as an A_i -module.
- (b) By section chapter I, §10, $T_p(M) = \varprojlim_i \ker p_M^n$ where $p_M : M \rightarrow M$ is the multiplication by p mapping from M onto itself. We can define the action of $\mathbb{Z}/p^{i+1}\mathbb{Z}$ on M by multiplication of $[x]_{p^{i+1}}$. We also note that for some $m \in M$, $[x]_{p^i} m = [x]_{p^i} m + kp_M^i m = [x]_{p^i} m + kp^i m = [x]_{p^{i+1}} m$. Therefore, if we take $A_i = \mathbb{Z}/p^i\mathbb{Z}$ in part (a) of this question, the diagram commutes and $T_p(M)$ is a module over $\varprojlim \mathbb{Z}/p^i\mathbb{Z} = \mathbb{Z}_p$.

- (c) By (a) and (b) and the distributivity of multiplication by p , $T_p(M \oplus N)$ is a \mathbb{Z}_p -module and so is $T_p(M) \oplus T_p(N)$. There is a homomorphism between the former and the later defined by $(m_1 + n_1, \dots) \mapsto (m_1, \dots) + (n_1, \dots)$.

Direct limits

- (19) By definition, if $a_k = 0$ for all k , the $a \sim 0$ which implies $f_{ij}(a) = f_{kj}(0) = 0$ for all $j \geq n$ for some $n \in I$.
- (20) Let $\{f_{(a,b),(c,d)}\}_{(a,b),(c,d) \in I \times I}$ be the given $I \times I$ -indexed direct family of morphisms. Let $f_{ij}^k = f_{(k,i),(k,j)} : A_{ki} \rightarrow A_{kj}$ and $g_{ij}^k = f_{(i,k),(j,k)} : A_{ik} \rightarrow A_{jk}$. By definition $\{f_{ij}^k\}$ and $\{g_{ij}^k\}$ form a direct family of morphisms. Let $A^{(i)} = \lim_j A_{ij}$ and let $N^{(i)}$ be an ideal/normal subgroup generated by the elements

$$x_{jk} = (0, \dots, 0, x, \dots, 0, -f_{jk}^i(x), 0, \dots),$$

where x and $-f_{jk}^i(x)$ are the j -th and k -th components of x_{jk} resp. Let $[x]_i = x \bmod N^{(i)}$. Define the map $\mu_{ij} : A^{(i)} \rightarrow A^{(j)}$ by

$$\mu_{ij}([x]_i) = [g_{ij}^k(x)]_j,$$

where $x \in A_{rk}$ for some r . Then $\mu_{ii}([x]_i) = [g_{ii}^k(x)]_i = [x]_i$ and for $i < m < j$

$$\begin{aligned} \mu_{ij}([x]_i) &= [g_{ij}^k(x)]_j \\ &= [g_{mj}^k \circ g_{im}^k(x)]_j \\ &= \mu_{mj}([g_{im}^k(x)]_m) \\ &= \mu_{mj} \circ \mu_{im}([x]_i). \end{aligned}$$

Hence $\{\mu_{ij}\}$ form a direct family of morphism and $\lim_i \lim_j A_{ij}$ exists. By symmetry $\lim_j \lim_i A_{ij}$ also exists.

Now suppose A is the group of infinite dimensional matrices $\{a_{ij}\}$ where $a_{ij} \in A_{ij}$ under component-wise group operation, and let N be the ideal generated by the matrices

$$X_{ijkl} = \begin{bmatrix} 0 & \dots & 0 & \dots & 0 & 0 & \dots \\ \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots \\ 0 & \dots & x & \dots & 0 & 0 & \dots \\ \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots \\ 0 & \dots & 0 & \dots & -f_{ij}^k(g_{ik}^l x) & 0 & \dots \\ \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots \end{bmatrix}$$

where $i \leq j$ and $i \leq k$ and x is the (i, l) -th entry and $-f_{ij}^k(g_{ik}^l x) = -g_{ik}^l(f_{ij}^i x)$ is the (k, j) -th entry of X_{ijkl} . From the description above, it is clear that both direct limits are naturally isomorphic to A/N .

The case for inverse limits is also similar. Let $\{f_{(a,b),(c,d)}\}_{(a,b),(c,d) \in I \times I}$ be the given $I \times I$ -indexed direct family of morphisms. Let $f_{ij}^k = f_{(k,i),(k,j)} : A_{ki} \rightarrow A_{kj}$ and $g_{ij}^k = f_{(i,k),(j,k)} : A_{ik} \rightarrow A_{jk}$ for all $j \leq i$. Let $A^{(i)} = \varprojlim_j A_{ij}$ with projections $\pi_j^{(i)} : A^{(i)} \rightarrow A_{ij}$, $(\dots, x_j, \dots) \mapsto x_j$. Then there are maps $v_{ijk} : A^{(i)} \rightarrow A_{kj}$ for some $k \leq i$ and all $j \in I$ defined by

$$v_{ijk}(x) = g_{ik}^j(\pi_j^{(i)}(x)).$$

By universality, there is a unique map $v_{ik} : A^{(i)} \rightarrow A^{(k)}$ for fixed i, k such that $v_{ijk} = \pi_j^{(k)} \circ v_{ik}$. We see that these maps are defined as

$$v_{ik}(x_0, x_1, \dots) \mapsto (g_{ik}^0(x_0), g_{ik}^1(x_1), \dots).$$

Since, g_{ik}^j form a directed family of morphisms, $A^{(i)}$ form a directed family and thus posses an inverse limit. By symmetry, $\varprojlim_i \varprojlim_j A_{ij}$ also exists. For fixed $i \leq k, j \leq l$, since $g_{ki}^j \circ f_{lj}^k = f_{lj}^i \circ g_{ki}^l$, the two inverse limits are naturally isomorphic.

(21)