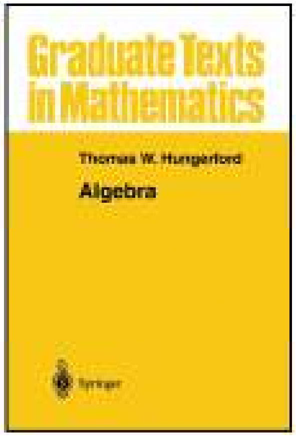
Modern Algebra

Chapter IX. The Structure of Rings

IX.1. Simple and Primitive Rings—Proofs of Theorems



Lemma IX.1.A

Lemma IX.1.A. Every simple module A is cyclic. In fact, $A = Ra$ for every nonzero $a \in A$.

Proof. First, Ra is a submodule of A by Theorem IV.1.5(i). Consider $B = \{c \in A \mid Rc = \{0\}\}$. Notice that $c_1, c_2 \in B$ implies $R(c_1 - c_2) = Rc_1 - Rc_2 = \{0\} - \{0\} = \{0\}$, so $c_1 - c_2 \in B$ and B is a subgroup of A (by Theorem I.2.5). By Definition IV.1.3, "submodule," B is a submodule of A (i.e., a sub-R-module of A). Since A is simple, then Ra is either $\{0\}$ of A and similarly for B. Also, since A is simple, then by Definition IX.1.1, $RA \neq \{0\}$; but $RB = \{0\}$ and we must have $B \neq A$. This implies that $B = \{0\}$ and so $Ra = \{0\}$ only when $a = 0$. So for all $a \in A$ where $a \neq 0$ we must have $Ra = A$, as claimed. Now the cyclic submodule of A generated by a consists of $\{ra + na \mid r \in Rmb \in \mathbb{Z}\}$ by Theorem IV.1.5(ii). But $Ra = A$ and so Ra includes all of $\{ra + na \mid r \in Rmb \in \mathbb{Z}\}$ and hence R-module A is cyclic and generated by a. □

Lemma IX.1.B

Lemma IX.1.B. Let $A = Ra$ be a cyclic R-module. Define $\theta : R \to A$ as $\theta(r) = ra$. Then $R/\text{Ker}(\theta)$ (and hence A) has no proper submodules if and only if $\text{Ker}(\theta)$ is a maximal left ideal of R.

Proof. Define $\theta : R \to A$ as $\theta(r) = ra$. By Theorem IV.1.5(i), θ is an R-module epimorphism (onto homomorphism). The kernel of θ is its kernel as a homomorphism of abelian groups (by definition, see Section IV.1) and so the kernel of θ determines a subgroup of the additive abelian group of R by Exercise I.2.9(a). For $b \in \text{Ker}(\theta)$ and $r \in R$ we have $rb \in \text{Ker}(\theta)$ since $\theta(rb) = (rb)a = r(ba) = r\theta(b) = r0 = 0$. So by Definition IV.1.3, $I = \text{Ker}(\theta)$ is a submodule of A. By the First Isomorphism Theorem (Theorem IV.1.7), $R/I = R/\text{Ker}(\theta) \cong A$. By Theorem IV.1.10, every submodule of R/I is of the form J/I, where J is a left ideal of R that contains $I = \text{Ker}(\theta)$. So module $R/\text{Ker}(\theta) = R/I$ (and hence A since $R/I \cong A$) has no proper submodules if and only if $I = \text{Ker}$ is a maximal left ideal of R. □

Theorem IX.1.3

Theorem IX.1.3. A left module A over ring R is simple if and only if A is isomorphic to R/I for some regular maximal left ideal I. This holds also if we replace "left" with "right."

Proof. Suppose A is simple. Then by Note IX.1.A, $A = Ra \cong R/I$ where U is some maximal left ideal. Since $A = Ra$ then $a = ea$ for some $e \in R$. So for any $r \in R$, $ra = req$ or $(r - re)a = 0$, whence $r - re \in \text{Ker}(\theta) = I$ where $\theta : R \to A$ is the epimorphism of Lemma IX.1.B defined as $\theta(r) = ra$. Therefore I is regular.

Suppose I is a regular maximal left ideal of R such that $A \cong R/I$ is of the form J/I where J is a left ideal of R that contains I. So module $R/I \cong A$ has no proper submodules since I is a maximal left ideal. So to show that $A \cong R/I$ is simple we need to show that $RA = R(R/I) \neq \{0\}$.

Theorem IX.1.3 (continued)

Theorem IX.1.3. A left module A over ring R is simple if and only if A is isomorphic to R/I for some regular maximal left ideal I. This holds also if we replace "left" with "right."

Proof (continued). ASSUME $R(R/I) = \{0\}$. Then for all $r \in R$, $r(e + I) \in R(R/I)$, where $r - re \in I$ by the regularity of I, and so $r(e + 1) = I$ (the identity in R/I), or $re + I = I$ or $re \in I$. Since $r - re \in I$, then $r \in I$ and so $R = I$. But this CONTRADICTS the definition maximal ideal (we need $I \neq R$; see Definition III.2.7 of maximal ideal). So the assumption that $R(R/I) = \{0\}$ is false and we must have $RA = R(R/I) \neq \{0\}$. Therefore by Definition IX.1.1, A is simple. □

Theorem IX.1.4

Theorem IX.1.4. Let B be a subset of a left module A over a ring R. Then $\mathcal{A}(B) = \{r \in R \mid rb = 0 \text{ for all } b \in B\}$ is a left ideal of R. If B is a submodule of A, then $\mathcal{A}(B)$ is an (two sided) ideal.

Proof. Let $r \in R$ and $s \in \mathcal{A}(B)$. Then $sb = 0$ for all $b \in B$ and so $(rs)b = r(sb) = r0 = 0$ for all $b \in B$; i.e., $rs \in \mathcal{A}(B)$. So $\mathcal{A}(B)$ is a left ideal of R.

Suppose B is a submodule of A. If $r \in R$ and $s \in \mathcal{A}(B)$, then for every $b \in B$ we have $(sr)b = s(rb) = s0 = 0$ since $rb \in B$ because B is a submodule of A (see Definition IV.1.3). Consequently $sr \in \mathcal{A}(B)$ and so $\mathcal{A}(B)$ is also a right ideal and hence a (two sided) ideal. □

Proposition IX.1.6

Proposition IX.1.6. A simple ring R with identity is primitive.

Proof. By Theorem III.2.18, R contains a maximal left ideal I. Since R has an identity then ideal I is regular (use $e = 1_R$ in Definition IX.1.2, "regular ideal"). Whence left R-module R/I is (isomorphic to) a simple R-module by Theorem IX.1.3. Now the annihilator $\mathcal{A}(R/I)$ is a (left) ideal of R by Theorem IX.1.4. Since R is simple by hypothesis, then $\mathcal{A}(R/I)$ must be either $\{0\}$ or R. Since I is a maximal ideal in R then $I \neq R$ (see Definition III.2.17 of maximal ideal) and so $R/I \neq \{0\}$. So 1_R cannot be in $\mathcal{A}(R/I)$; that is, $\mathcal{A}(R/I) \neq R$. Hence it must be that $\mathcal{A}(R/I) = \{0\}$. Therefore, left R-module R/I is faithful and ring R is primitive by Definition IX.1.5. □

Proposition IX.1.7

Proposition IX.1.7. A commutative ring R is primitive if and only if R is a field.

Proof. Suppose R is a field. Then R is a division ring and by the first example in this section of class notes, R is simple. Since a field has an identity, then by Proposition IX.1.6, R is primitive.

Suppose R is a commutative primitive ring. By Definition IX.1.5, this means there is a simple faithful (left) R-module A; that is, simple R-module A satisfies $\mathcal{A}(A) = \{0\}$. By Theorem IX.1.3, $A \cong R/I$ for some regular maximal left ideal I. Since R is commutative then I is a (two sided) ideal. Also $I \subset \mathcal{A}(R/I) = \mathcal{A}(A) = \{0\}$, so we must have $I = \{0\}$. Since $I = \{0\}$ is regular, by Definition IX.1.2 there is $e \in R$ such that $r - re = r - er \in I$, or $r = re = er$ for all $r \in R$. That is, $e = 1_R$ is an identity for R. Since $I = \{0\}$ is maximal by Corollary III.2.21 (the (iii) implies (i) part), R is a field. □

Lemma IX.1.C

Lemma IX.1.C/Example. For V a vector space over a division ring D, the endomorphism ring $\mathrm{Hom}_D(V,V)$ is a dense subring of itself.

Proof. Let $n \in \mathbb{N}$, $\{u_1, u_2, \ldots, u_n\}$ be a linearly independent subset of V, and $\{v_1, v_2, \ldots, v_n\} \subset V$. By Theorem IV.2.4 there is a basis U of V that contains $u_1, u_2, \ldots, u_n$. Define the map $\theta : V \to V$ by $\theta(u_i) = v_i$ for $i = 1, 2, \ldots, n$ and $\theta(u) = 0$ for $u \in U \setminus \{u_1, u_2, \ldots, u_n\}$. By Theorem IV.2.4, V is a free D-module. By Theorem IV.2.1(iv), θ is a homomorphism (see the proof of (i) implies (iv)). That is, $\theta \in \mathrm{Hom}_D(V,V)$ and so $\mathrm{Hom}_D(V,V)$ is a dense subring of itself by Definition IV.1.8. □

Theorem IX.1.9

Theorem IX.1.9. Let R be a dense ring of endomorphisms of a vector space V over a division ring D. Then R is left (respectively, right) Artinian if and only if $\dim_D(V)$ is finite, in which case $R = \mathrm{Hom}_D(V,V)$.

Proof. Let R be Artinian. ASSUME $\dim_D(V)$ is infinite. Then there exists an infinite linearly independent subset $\{u_1, u_2, \ldots\}$ of V. By Exercise IV.1.7(c), V is a left $\mathrm{Hom}_D(V,V)$-module; since R is a subring of $\mathrm{Hom}_D(V,V)$ (by Definition IX.1.8, "dense ring of endomorphisms") then V is also a left R-module (see Definition IV.1., "R-module"). For each $n \in \mathbb{N}$ let I_n be the left annihilator in R of the set $\{u_1, u_2, \ldots, u_n\}$. Then $I_1 \supset I_2 \supset \cdots$ is a descending chain of left ideal. Let w be any nonzero element of V. Since $\{u_1, u_2, \ldots, u_{n+1}\}$ is linearly independent for each $n \in \mathbb{N}$ and R is dense, then (by Definition IX.1.8, "sense ring of endomorphisms") there is $\theta \in R$ such that $\theta(u_i) = 0$ for $i = 1, 2, \ldots, n$ and $\theta(u_{n+1}) = w \neq 0$. Then $\theta \in I_n$ (since θ annihilates $\{u_1, u_2, \ldots, u_n\}$) but $\theta \notin I_{n+1}$. So $I_n \supset I_{n+1}$ and $I_n \neq I_{n+1}$.

Theorem IX.1.9 (continued)

Proof (continued). But then $I_1 \supset I_2 \supset \cdots$ is a "properly descending" chain and so R cannot be left Artinian, a CONTRADICTION. So the assumption that $\dim_D(V)$ is finite is false. Hence if R is Artinian then $\dim_D(V)$ is finite.

Suppose $\dim_D(V)$ is finite. Then V has a finite basis $\{v_1, v_2, \ldots, v_m\}$. If f is any element of $\mathrm{hom}_D(V,V)$ then f is completely determines by its action on $v_1, v_2, \ldots, v_m$. Since R is dense then, by Definition IX.1.8, there exists $\theta \in R$ such that $\theta(v_i) = f(v_i)$ for $i = 1, 2, \ldots, m$. Whence $f = \theta \in R$ and so $\mathrm{Hom}_D(V,V) \in R$. But dense ring of endomorphisms R is a subring of $\mathrm{Hom}_D(V,V)$ (see Definition IX.1.8 again), so $\mathrm{Hom}_D(V,V)$ is isomorphic to the ring of all $n \times n$ matrices with entries from D. By Corollary VIII.1.12, $\mathrm{Mat}_n(D)$ is Artinian. Therefore, since R is a subring of $\mathrm{Hom}_D(V,V)$ then R is Artinian. □

Lemma IX.1.10 (Schur)

Lemma IX.1.10. (Schur) Let A be a simple module over a ring R and let B be any R-module.

(i) Every nonzero R-module homomorphism $f : A \to B$ is a monomorphism (one to one);

(ii) every nonzero R-module homomorphism $f : B \to A$ is an epimorphism (onto);

(iii) the endomorphism ring $D = \mathrm{Hom}_R(A,A)$ is a division ring.

Proof. (i) The kernel of f is its kernel as a homomorphism of abelian groups (by definition, see Section IV.1) and so the kernel of f determines a subgroup of the additive abelian group of R by Exercise I.2.9(a). For $c \in \mathrm{Ker}(f)$ and $r \in R$ we have $rc \in \mathrm{Ker}(f)$ since $f(rc) = rf(c) = r0 = 0$ (see Definition IV.1.2, "R-module homomorphism"). So by Definition IV.1.3, $\mathrm{Ker}(f)$ is a submodule of A. Since f is nonzero then $\mathrm{Ker}(f) \neq A$.

Lemma IX.1.10 (Schur) continued

Proof (continued). Since A is simple then it must be that $\mathrm{Ker}(f) = \{0\}$ and so f is a monomorphism (one to one) by Theorem I.2.3 (see also page 170 of Hungerford and the example in the class notes after Definition IV.1.3), as claimed.

(ii) $\mathrm{Im}(g)$ is a submodule of A by Exercise I.2.9(b) (see also the example in the class notes after Definition IV.1.3). Since g is nonzero, $\mathrm{Im}(g) \neq \{0\}$. So $\mathrm{Im}(g)$ is a nonzero submodule of A and since A is simple it must be that $\mathrm{Im}(f) = A$. That is, g is an epimorphism (onto), as claimed.

(iii) We use parts (i) and (ii). Let $j \in D = \mathrm{Hom}_R(A, A)$ with $h \neq 0$. By (i), h is onto to ne (injective) and by (ii) f is onto (surjective), so h is an isomorphism. By Theorem I.2.3(ii) (see also page 170 of Hungerford) h has a two-sided inverse $h^{-1} \in \mathrm{Hom}_R(A, A) = D$. Since h is an arbitrary nonzero element of D, then D is a division ring. □

Lemma IX.1.11

Lemma IX.1.11. Let A be a simple module over a ring R. Consider A as a vector space over the division ring $D = \mathrm{Hom}_R(A, A)$. If V is a finite dimensional D-subspace of the D-vector space A and $a \in A \setminus V$, then there exists $r \in R$ such that $ra \neq 0$ and $rV = 0$.

Proof. We give an induction proof on $n = \dim_D(V)$.

Let $n = 0$. Then $V = \{0\}$ and so $a \in A \setminus V$ implies $a \neq 0$. Since A is simple, then by Lemma IX.1.A, $A = Ra$. So there is some $r \in R$ such that $ra = a \neq 0$ and $rV = v\{0\} = \{0\}$, and the claim holds for $n = \dim_D(V) = 0$.

Now suppose $\dim_D(V) = n \in \mathbb{N}$ and that the theorem holds for dimensions $0, 1, \ldots, n-1$. Let $\{u_1, u_2, \ldots, u_{n-1}, u\}$ be a D-basis of V (which exists by Theorem IV.2.4) and let W be the $(n-1)$-dimensional D-subspace $W = \mathrm{span}\{u_1, u_2, \ldots, u_{n-1}\}$ (with $W = \{0\}$ if $n = 1$).

Lemma IX.1.11 (continued 1)

Proof (continued). Since $\{u_1, u_2, \ldots, u_{n-1}, u\}$ is a basis then it is linearly independent and so $W \cap Du = \{0\}$ (notice that Du itself is a vector space; it is the span of $\{u\}$). So $V = W \oplus Du$ by Theorem IV.1.5. The left annihilator $I = \mathcal{A}(W)$ in R of W is a left ideal o fR by Theorem IX.1.4. By Exercise IV.1.3(a), Iu is an R-submodule of A. Since $u \in A \setminus W$ and $\dim_D(W) = n-1$ then by the *induction hypothesis* there is $r \in R$ such that $ru \neq 0$ and $rW = \{0\}$ (that is, $r \in I = \mathcal{A}(W)$). This implies $0 \neq ru \in Iu$ is a nonzero R-submodule of A then $A = Iu$. Notice that the induction hypothesis has given us that: for $u \in A$ we have that $u \notin W$ (where $\dim_D(W) = n-1$) implies there is $r \in I = \mathcal{A}(W)$ such that $ru \neq 0$. The contrapositive of this is that:

For $v \in A$, if for all $r \in I = \mathcal{A}(W)$ we have $rv = 0$ then $v \in W$. (*)

We must find $r \in R$ such that $ra \neq 0$ and $rV = \{0\}$. ASSUME no such r exists. Then define $\theta : A \to A$ as follows. For $ru \in Iu = A$ let $\theta(ru) = ra \in A$.

Lemma IX.1.11 (continued 2)

Proof (continued). We claim that θ is well-defined (that is, if $r_1u = r_2u$ for $r_1, r_2 \in I = \mathcal{A}(W)$, then $(r_1 - r_2)u = 0$, whence $(r_1 - r_2)V = (r_1 - r_2)(W \oplus Du) = \{0\}$ (since elements of $W \oplus Du$ are sums of elements of W, which $r_1 - r_2$ annihilates, and multiples of u of the form $du = d(u)$ for $d \in D = \mathrm{Hom}_R(A, A)$ so that $(r_1 - r_2)du = (r_1 - r_2)d(u) = d((r_1 - r_2)u) = d(0) = 0$). By the assumption (that no r exists such that $ra \neq 0$ and $rV = \{0\}$; but here we have $(r_1 - r_2)V = \{0\}$) we must have $(r_1 - r_2)a = 0$. Therefore $r_1a = r_2a$ or $r_1a = \theta(r_1u) = \theta(r_2u) = r_2a$, and θ is well-defined. Let $a_1, a_2 \in A$. Since $A = Iu$ then there is $r_1, r_2 \in I$ such that $a_1 = r_1u$ and $a_2 = r_2u$. So

$$\theta(a_1+a_2) = \theta(r_1u+r_2u) = \theta((r_1+r_2)u) = (r_1+r_2)a = r_1a+r_2a = \theta(r_1u)+\theta(r_2$$

Also, for $r' \in R$ and $a \in A = Iu$ (so that $a = ru$ for some $r \in I$) we have

$$\theta(r'a) = \theta(r'(ru)) = \theta((r'r)u) = (r'r)a = r'(ra) = r'\theta(ru) = r'\theta(a).$$

Lemma IX.1.11 (continued 3)

Proof (continued). Therefore θ is an R-module homomorphism mapping $A \to A$ (by Definition IV.1.2); that is, $\theta \in \mathrm{Hom}_R(A, A) = D$. Then for every $r \in I$,

$$0 = ra - ra = \theta(ru) - ra = r\theta(u) - ra = r(\theta(u) - a).$$

So by $(*)$, $\theta(u) - a = \theta u - a \in W$ and $a - \theta u \in W$. Notice that $\theta u = \theta(u) \in Du$ since $\theta \in D = \mathrm{Hom}_R(A, A)$. Consequently $a = (a - \theta u) + \theta u \in W \oplus Du = V$. But this is a CONTRADICTION to the fact that $a \in A \setminus V$. So the assumption that no such r exists is false, and hence there exists $r \in R$ such that $ra \neq 0$ and $rV = \{0\}$. That is, the result holds for $\dim_D(V) = n$ and so holds for all $n \in \mathbb{N} \cup \{0\}$ by induction. □

Theorem IX.1.12. Jacobson Density Theorem

Theorem IX.1.12. Jacobson Density Theorem.
Let R be a primitive ring and A a faithful simple R-module. consider A as a vector space over the division ring $\mathrm{hom}_R(A, A) = D$. Then R is isomorphic to a dense ring of endomorphisms of the D-vector space A.

Proof. For each $r \in R$ the map $\alpha_r : A \to A$ given by $\alpha_r(A) = ra$ is a D-endomorphism of A (for $a_1, a_2 \in A$ we have $\alpha_r(a_1 + a_2) = r(a_1 + a_2) = ra_1 + ra_2 = \alpha_r(a_1) + \alpha_r(a_2)$ and for $a \in A$ and $\theta \in D = \mathrm{Hom}_R(A, A)$ we have

$$\begin{aligned} \alpha_r(\theta a) &= \alpha_r(\theta(a)) = r\theta(a) \\ &= \theta(ra) \text{ since } \theta \in \mathrm{Hom}_R(A, A) \\ &= \theta(\alpha_r(a)), \end{aligned}$$

so by Definition IV.1.2 α_r is a homomorphism). That is, $\alpha_r \in \mathrm{Hom}_D(A, A)$. Furthermore, for all $r, s \in R$ we have $\alpha_{r+s} = \alpha_r + \alpha_s$ and $\alpha_{rs} = \alpha_r\alpha_s$.

Theorem IX.1.12. Jacobson Density Theorem (continued 1)

Proof (continued). Consequently, the map $\alpha : R \to \mathrm{Hom}_D(A, A)$ defined by $\alpha(r) = \alpha_r$ is a homomorphism of rings. Since A is a faithful R-module (that is, $\mathcal{A}(A) = \{0\}$), $\alpha_r = 0 \in \mathrm{Hom}_D(A, A)$ if an only if $r \in \mathcal{A}(A) = \{0\}$. So $\mathrm{Ker}(\alpha) = \{0\}$ and α is a monomorphism (one to one; by Theorem I.2.3(i)). Whence R is isomorphic to the subring $\mathrm{Im}(\alpha)$ of $\mathrm{Hom}_D(A, A)$.

Now we show that $\mathrm{Im}(\alpha)$ is a dense subring of $\mathrm{Hom}_D(A, A)$. So given any D-linearly independent subset $U = \{u_1, U_2, \ldots, u_n\}$ of A and any subset $\{v_1, v_2, \ldots, v_n\}$ of A, we must find $\alpha_r \in \mathrm{Im}(\alpha)$ such that $\alpha_r(u_i) = v_i$ for $i = 1, 2, \ldots, n$. Here we go. For each $i = 1, 2, \ldots, n$, let V_i be the D-subspace of A spanned by $\{u_1, u_2, \ldots, u_{i-1}, u_{i+1}, \ldots u_n\}$. Since U is D-linearly independent then $u_i \in V_i$. Consequently (since A is simple by Definition IX.1.5 of "primitive ring"), by Lemma IX.1.11 there exists $r_i \in R$ such that $r_iu_i \neq 0$ and $r_iV_i = \{0\}$.

Theorem IX.1.12. Jacobson Density Theorem (continued 2)

Proof (continued). Applying Lemma IX.1.11 to D-subspace $V = \{0\}$ of A and nonzero $r_iu_i \in A \setminus V$, there exists $s_i \in R$ such that $s_ir_iu_i \neq 0$ and $s_i0 = 0$. Since $s_ir_iu_i \neq 0$, the R-submodule Rr_iu_i of A is nonzero. But A is simple (by the definition of "primitive ring" R), so it must be that $Rr_iu_i = A$. Therefore there exists $t_i \in R$ such that $t_ir_iu_i = v_i$. Define $r = t_1r_1 + t_2r_2 + \cdots + t_nr_n \in R$. By definition of V_j, we have for $i \neq j$ that $u_i \in V_j$ and so for $i \neq j$ we also have $t_jr_ju_i \in t_j(r_jV_j) = t_j\{0\} = \{0\}$ (since $r_jV_j = \{0\}$ by the choice of r_j above). Consequently for each $i = 1, 2, \ldots, n$ we have

$$\alpha_r(u_i) = ru_i = (t_1r_1 + t_2r_2 + \cdots + t_nr_n)u_i = t_ir_iu_i = v_i.$$

So, by Definition IX.1.8, "dense ring of endomorphisms," $\mathrm{Im}(\alpha)$ is a dense ring of endomorphisms of the D-vector space A. Since R is isomorphic to $\mathrm{Im}(\alpha)$ (under isomorphism α), the claim follows. □

Corollary IX.1.13

Corollary IX.1.13. If R is a primitive ring, then for some division ring D either R is isomorphic to the endomorphism ring of a finite dimensional vector space over D or for every $m \in \mathbb{N}$ there is subring R_m of R and an epimorphism of rings mapping $R_m \to \mathrm{Hom}_D(V_m, V_m)$ where V_m is an n-dimensional vector space over D.

Proof. In the notation of the Jacobson Density Theorem (Theorem IX.1.12) with A as the faithful simple R-module and $D = \mathrm{Hom}_R(A, A)$, we have $\alpha : R \to \mathrm{Hom}_D(A, A)$ is a monomorphism such that $R \cong \mathrm{Im}(\alpha)$ and $\mathrm{Im}(\alpha)$ is dense in $\mathrm{Hom}_D(A, A)$. If $\dim_D(A) = n$ is finite, then $\mathrm{Im}(\alpha) = \mathrm{Hom}_D(A, A)$ by Theorem IX.1.9 (this also gives that $\mathrm{Im}(\alpha)$ is left Artinian). So the first conclusion holds.

If $\dim_D(A)$ is infinite and $\{u_1, u_2, \ldots\}$ is an infinite linearly independent set, then let V_m be the m-dimensional D-subspace of A spanned by $\{u_1, u_2, \ldots, u_m\}$. Define $R_n = \{r \in R \mid rV_m \subset V_m\}$.

Corollary IX.1.13 (continued)

Corollary IX.1.13. If R is a primitive ring, then for some division ring D either R is isomorphic to the endomorphism ring of a finite dimensional vector space over D or for every $m \in \mathbb{N}$ there is subring R_m of R and an epimorphism of rings mapping $R_m \to \mathrm{Hom}_D(V_m, V_m)$ where V_m is an n-dimensional vector space over D.

Proof (continued). If $r_1, r_2 \in R_m$ then $(r_1 + r_2)V_m = r_1 V_m + r_2 V_m \subset V_m$ since $r_1 V_m$ and $r_2 V_m$ are subset of V_m (and V_m is closed under addition), and $(r_1 r_1)V_m = r_1(r_2 V_m) \subset V_m$ since $r_2 V_m \subset V_m$ and $r_1 V_m \subset V_m$. So R_m is a subring of R. Define $\beta : R_m \to \mathrm{Hom}_D(V_m, V_m)$ as the restriction of α_r to V_m: $\beta(r) = \alpha_r|_{V_m}$. By Exercise IX.1.A, β is a well-defined ring epimorphism and the second claim holds. □

Theorem IX.1.14. The Wedderburn-Artin Theorem for Simple Artinian Rings

Theorem IX.1.14. The Wedderburn-Artin Theorem for Simple Artinian Rings.
The following conditions on a left Artinian ring R are equivalent:

(i) R is simple;

(ii) R is primitive;

(iii) R is isomorphic to the endomorphism ring of a nonzero finite dimensional space V over a division ring D;

(iv) for some $b \in \mathbb{N}$, R is isomorphic to the ring of all $n \times n$ matrices over a division ring.

Proof. (i)⇒(ii). Let $I = \{r \in R \mid Rr = \{0\}\}$. Then I is the right annihilator of R (treating ring R as an R-module) and since R is a submodule of itself then I is an ideal of R by Theorem IX.1.4. Since R is hypothesized to be simple then either $I = R$ or $I = \{0\}$.

Theorem IX.1.14. The Wedderburn-Artin Theorem for Simple Artinian Rings (continued)

Proof (continued). Since R is a simple ring then (by Definition IX.1.1) $R^2 \neq \{0\}$ and we cannot have $I = R$ (or else $Rr = \{0\}$ for all $r \in R$; that is, $R^2 = \{0\}$). Hence $I = \{0\}$. Since R is left Artinian by hypothesis, the set of all nonzero left ideals of R contains a minimal left ideal J by Theorem VIII.1.4. Now J has no proper R-submodules (notice that an R-submodule of J would be a left ideal of R). We claim that annihilator $\mathcal{A}(J) = \{0\}$ in R. ASSUME $\mathcal{A}(J) \neq \{0\}$. By Theorem IX.1.4, the left annihilator $\mathcal{A}(J)$ is a left ideal of R. Since R is simple then we must have $\mathcal{A}(J) = R$. Then $Ru = 0$ for every nonzero $u \in J$. Consequently, each such nonzero u is in $I = \{0\}$, a CONTRADICTION. Therefore $\mathcal{A}(J) = \{0\}$. Also $RJ \neq \{0\}$ (or else $A(J) = R \neq \{0\}$). Thus J is a faithful simple R-module and so by Definition IX.1.5, "primitive ring," R is primitive.

Theorem IX.1.14. The Wedderburn-Artin Theorem for Simple Artinian Rings (continued)

Proof (continued). (ii)$\Rightarrow$(iii). Since R is primitive by hypothesis, then by the Jacobson Density Theorem (Theorem IX.1.12) R is isomorphic to a dense ring T of endomorphisms of a vector space V over a division ring D. Since R is left Artinian by hypothesis then $R \cong T = \mathrm{Hom}_D(V,V)$ and $\dim_D(V)$ is finite, as claimed.

(iii)$\Leftrightarrow$(iv). By Theorem VII.1.4, $\mathrm{Hom}_D(V,V)$ is isomorphic to a ring of $n \times n$ matrices with entries from a division ring.

(iv)$\Rightarrow$(i). Exercise III.2.9(a) implies R has no proper ideals and so, by Definition IX.1.1, R is simple. □

Lemma IX.1.15

Lemma IX.1.15. Let V be a finite dimensional vector space over a division ring D. If A and B are simple faithful modules over the endomorphism ring $R = \mathrm{Hom}_D(V,V)$, then A and B are isomorphic R-modules.

Proof. Since V is finite dimensional (say $\dim_D(V) = n$), by Theorem VII.1.4 $R = \mathrm{Hom}_D(V,V)$ is isomorphic to a ring of $n \times n$ matrices over a division ring. By Corollary VIII.1.12, R is Artinian (and so satisfies the descending chain condition). Then by Theorem VIII.1.4, R contains a (nonzero) minimal left ideal I. Since A is faithful then (by Definition IX.1.5) the annihilator $\mathcal{A}(A) = \{0\}$. So there exists $a \in A$ such that $Ia \neq \{0\}$. By Exercise IV.1.3, Ia is a nonzero submodule of A. Since A is simple, then $Ia = A$. Define $\theta : I \to Ia = A$ as $\theta(i) = ia$. Then θ is a nonzero R-module epimorphism; that is, $\theta \in \mathrm{Hom}_R(A,A)$. By Lemma IX.1.10, θ is a monomorphism and epimorphism, and so is an isomorphism. That is, $A \cong I$. Similarly, $B \cong I$ and so $A \cong B$. □

Lemma IX.1.16

Lemma IX.1.16. Let V be a nonzero vector space over a division ring D and let R be the endomorphism ring $\mathrm{Hom}_D(V,V)$. If $g : V \to V$ is a homomorphism of additive groups such that $gr = rg$ for all $r \in R$, then there exists $d \in D$ such that $g(v) = dv$ for all $v \in V$.

Proof. Let u be a nonzero element of V. We claim that u and $g(u)$ are linearly independent over D. If $\dim_D(V) = 1$ then this is trivial, so we now consider the case $\dim_D(V) \geq 2$. ASSUME $\{i, g(u)\}$ is linearly independent. Since R is dense in itself by Lemma IX.1.C, then there is $r \in R$ such that $r(u) = ru = 0$ and $r(g(u)) = rg(u) \neq 0$. But by hypothesis $f(g(u)) = rg(u) = gr(u) = g(r(u)) = g(0) = 0$, a CONTRADICTION to the fact that $r(g(u)) \neq 0$. So the assumption is false and $\{u, g(u)\}$ is linearly independent.

Lemma IX.1.16 (continued)

Lemma IX.1.16. Let V be a nonzero vector space over a division ring D and let R be the endomorphism ring $\mathrm{Hom}_D(V,V)$. If $g : V \to V$ is a homomorphism of additive groups such that $gr = rg$ for all $r \in R$, then there exists $d \in D$ such that $g(v) = dv$ for all $v \in V$.

Proof (continued). Therefore for some $d \in D$, $g(u) = du$. If $v \in V$ then there exists $s \in R$ such that $s(u) = su = v$ because R is dense in itself. Consequently, since $s \in R = \mathrm{Hom}_D(V,V)$, then

$$g(v) = g(s(u)) = gs(u) = sg(u) = s(du) = ds(u) = dv,$$

and since v is arbitrary, the claim holds. □

Proposition IX.1.17

Proposition IX.1.17. Let V_1 and V_2 be vector spaces of finite dimension n over the division rings D_1 and D_2, respectively.

(i) If there is an isomorphism of rings $\mathrm{Hom}_{D_1}(V_1, V_2) \cong \mathrm{Hom}_{D_2}(V_2, V_2)$, then $\dim_{D_1}(V_1) = \dim_{D_2}(V_2)$ and D_1 is isomorphic to D_2.

(ii) If there is an isomorphism of rings $\mathrm{Mat}_{n_1}(D_1) \cong \mathrm{Mat}_{n_2}(D_2)$, then $n_1 = n_2$ and D_1 is isomorphic to D_2.

Proof. (i) It is argued in the example after Definition IX.1.5 that each V_i is a faithful $\mathrm{Hom}_{D_i}(V_i, V_i)$-module for $i = 1, 2$. Let $R = \mathrm{Hom}_{D_1}(V_1, V_1)$ and let σ be the hypothesized isomorphism, $\sigma : r = \mathrm{Hom}_{D_1}(V_1, V_1) \to \mathrm{Hom}_{D_2}(V_2, V_2)$. So V_2 is a faithful simple R-module (or $\mathrm{Hom}_{D_1}(V_1, V_1)$-module) by pullback along σ; that is,

$$rv - \sigma(r)v \text{ for } r \in R, v \in V_2. \qquad (*)$$

By Lemma IX.1.15 (with $A = V_1$ and $B = V_2$) there is an R-module isomorphism $\varphi : V_1 \to V_2$.

Proposition IX.1.17 (continued 1)

Proof (continued). For each $v \in V_1$ and $f \in R$, $\varphi(f(v)) = f\varphi(v) = \sigma(f)[\varphi(v)]$ by $(*)$. With $x \in V_2$ and $v = \varphi^{-1}(w)$ we then have $\varphi(f(\varphi^{-1}(w))) = \sigma(f)v$ for each $w \in V_2$ and $f \in R$. That is, $\varphi f \varphi^{-1} = \sigma(f)$ and this is a homomorphism (not necessarily an isomorphism since $f \in \mathrm{Hom}_{D_1}(V_1, V_1)$ is a homomorphism) of additive groups $V_2 \to V_2$. For each $d \in D_i$, let $\alpha_d : V_i \to V_i$ be the homomorphism of additive groups defined by the mapping $x \mapsto dx$ (for $i = 1, 2$). Now $\alpha_d = 0$ if and only if $d = 0$ (since $dx = 0$ for $d \neq 0$ implies $d^{-1}dx = d^{-1}0$ or $x = 0$ since d is in a division ring). For $f \in R = \mathrm{Hom}_{D_1}(V_1, V_1)$ and $d \in D_1$, we have for $x \in V_1$ that $f\alpha_d(x) = fdx = f(dx) = df(x) = \alpha_d f(x)$, so $f\alpha_d = \alpha_d f$. Consequently,

$$\begin{aligned}(\varphi\alpha_d\varphi^{-1})(\sigma f) &= \varphi\alpha_d\varphi^{-1}(\varphi f \varphi^{-1}) \text{ since } \varphi f \varphi^{-1} = \sigma(f) \\ &= \varphi\alpha_d f \varphi^{-1} = \varphi f \alpha_d \varphi^{-1} \text{ since } f\alpha_d = \alpha_d f \\ &= \varphi f \varphi^{-1}\varphi\alpha_d\varphi^{-1} = (\sigma f)(\varphi\alpha_d\varphi^{-1}) \text{ since } \varphi f \varphi^{-1} = \sigma f.\end{aligned}$$

Proposition IX.1.17 (continued 2)

Proof (continued). Now $g = \varphi\alpha_d\varphi^{-1} : V_2 \to V_2$ is a homomorphism and this last equation shows that $g(\sigma f) = \sigma f)g$ for all φf for every $\sigma f \in \mathrm{Hom}_{D_2}(V_2, V_2)$ (since σ is surjective [onto; it is an isomorphism], σf for $f \in \mathrm{Hom}_{D_1}(V_1, V_1)$ includes all elements of $\mathrm{Hom}_{D_2}(V)2, V_2)$). So by Lemma IX.1.16 (with $V = V_2$) implies that there exists $d^* \in D_2$ such that $g = \varphi\alpha_d\varphi^{-1} = \alpha_{d^*}$. Let $\tau : D_1 \to D_2$ be the map given by $\tau(d) = d^*$. Then for every $d \in D_1$, $g = \varphi\alpha_d\varphi^{-1} = \alpha_{d^*} = \alpha_{\tau(d)}$. We now show that $\tau : D_1 \to D_2$ is an isomorphism. If $d, d' \in D_1$ then $\tau(d + d') = (d + d')^*$ where $\varphi\alpha_{d+d'}\varphi^{-1} = \alpha_{(d+d')^*}$. As shown in the proof of Theorem IX.1.12, we have $\alpha_{d+d'} = \alpha_d + \alpha_{d'}$ and so

$$\varphi\alpha_{d+d'}\varphi^{-1} = \varphi(\alpha_d + \alpha_{d'})\varphi^{-1} = \varphi\alpha_d\varphi^{-1} + \varphi\alpha_{d'}\varphi^{-1}$$

$$= \alpha_{d^*} + \alpha_{(d')^*} = \alpha_{(d+d')^*},$$

so that $\tau(d + d') = (d + d')^* = d^* + (d')^*$.

Proposition IX.1.17 (continued 3)

Proof (continued). Similarly, as shown in the proof of Theorem IX.1.12, we have $\alpha_{dd'} = \alpha_d\alpha_{d'}$ and so

$$\alpha_{(dd')^*} = \varphi\alpha_{dd'}\varphi^{-1} = \varphi\alpha_d\alpha_{d'}\varphi^{-1} = (\varphi\alpha_d\varphi^{-1})(\varphi\alpha_{d'}\varphi^{-1}) = \alpha_{d^*}\alpha_{(d')^*}$$

so that $\tau(dd') = \tau(d)\tau(d')$. So τ is a ring homomorphism (by Definition III.1.7). Now suppose $d \neq d'$. then there is nonzero $v \in V_1$ such that $dv_1 \neq d'v_1$ (or else $dv_1 = d'v_1$ for all $v_1 \in V_1$ and so $(d - d')v_1 = 0$ for all $v_1 \in V_1$; if $d - d' \neq 0 \in D_2$ then $(d - d')^{-1}$ exists since D_2 is a division ring and so $(d - d')^{-1}(d - d')v_1 = (d - d')^{-1}0$ or $v_1 = 0$, a contradiction to the choice of v_1). So $\alpha_d \neq \alpha_{d'}$ because $\alpha_d v_1 = dv_1 \neq d'v_1 = \alpha_{d'}v_1$.

Proposition IX.1.17 (continued 4)

Proof (continued). Now $\varphi : V_1 \to V_2$ and $\varphi^{-1} : V_2 \to V_1$ are isomorphisms (and so are surjective/onto and injective/one to one) so for some $v_2 \in V_2$ we have $\varphi^{-1}v_2 = v_1$ and

$$\begin{aligned} \alpha_{\tau(d)}v_2 &= \varphi\alpha_d\varphi^{-1}v_2 = \varphi\alpha_d v_1 \\ &\neq \varphi\alpha_{d'}v_1 \text{ since } \varphi \text{ is one to one} \\ &= \varphi\alpha_{d'}\varphi^{-1}v_2 = \alpha_{\tau(d')}v_2, \end{aligned}$$

so $\alpha_{\tau(d)} \neq \alpha_{\tau(d')}$, or $\alpha_{d^*} \neq \alpha_{(d')^*}$. So $\alpha_{d^*} = \varphi\alpha_d\varphi^{-1} \neq \varphi\alpha_{d'}\varphi^{-1} = \alpha_{(d')^*}$. Since both α_{d^*} and $\alpha_{(d')^*}$ also map $V_2 \to V_2$, this means for some $v \in V_2$ we have $\alpha_{d^*}(v) \neq \alpha_{(d')^*}(v)$ or $d^*v \neq (d')^*v$. *If* $d^* = (d')^*$ then $d^*v = (d')^*v$ and so we must have $d^* \neq (d')^*$; that is, $\tau(d) \neq \tau(d')$. Hence τ is a monomorphism (one to one and onto homomorphism).

Proposition IX.1.17 (continued 5)

Proof (continued). Reversing the roles of D_1 and D_2 in the previous argument (and replacing φ and σ with φ^{-1} and σ^{-1}, respectively) yields that for every $d_2 \in D_2$ there exists $d_1 \in D_1$ such that $\varphi^{-1}\alpha_{d_2}\varphi = \alpha_{d_1} : V_1 \to V_1$, whence $\alpha_{d_2} = \varphi\alpha_{d_1}\varphi^{-1} = \alpha_{\tau(d_1)}$. So $\tau(d_1) = d_2$ and τ is surjective/onto. Hence $\tau : D_1 \to D_2$ is an isomorphism and so D_1 is isomorphic to D_2, as claimed.

Furthermore, for every $d \in D_1$ and $v \in V_1$,

$$\begin{aligned} \varphi(dv) &= \varphi\alpha_d(v) = \varphi\alpha_d\varphi^{-1}\varphi(v) \\ &= \alpha_{\tau(d)}\varphi(v) \text{ since } \alpha_{\tau(d)} = \varphi\alpha_d\varphi^{-1} \\ &= \tau(d)\varphi(v) \text{ by definition of } \alpha_{\tau(d)}. \qquad (**) \end{aligned}$$

Consider the sets $A = \{u_1, u_2, \ldots, u_k\}$ and $B = \{\varphi(u_1), \varphi(u_2), \ldots, \varphi(u_k)\}$. Suppose A is D_1-linearly independent; then for $r_1, r_2, \ldots, r_k \in D_1$ we have that $r_1u_1 + r_2u_2 + \cdots + r_ku_k = 0$ implies that $r_1 = r_2 = \cdots = r_k = 0$.

Proposition IX.1.17 (continued 6)

Proof (continued). Suppose $s_1\varphi(u_1) + s_2\varphi(u_2) + \cdots + s_k\varphi(u_k) = 0$ for $s_1, s_2, \ldots, s_k \in D_2$. Since $\tau : D_1 \to D_2$ is an isomorphism, then there are $r_1, r_2, \ldots, r_k \in D_1$ such that $\tau(r_1) = s_1, \tau(r_2) = s_2, \ldots, \tau(r_k) = s_k$ and so $\tau(r_1)\varphi(u_1) + \tau(r_2)\varphi(u_2) + \cdots + \tau(r_k)\varphi(u_k) = 0$, or by $(**)$, $\varphi(r_1u_1) + \varphi(r_2u_2) + \cdots + \varphi(r_ku_k) = 0$, or since φ is a homomorphism, $\varphi(r_1u_1 + r_2u_2 + \cdots + r_ku_n) = 0$. Since φ is an isomorphism, it is injective (one to one) and so $r_1u_1 + r_2u_2 + \cdots + r_ku_k = 0$. Since A is linearly independent, then $r_1 = r_2 = \cdots = r_k = 0$. Since τ is a homomorphism, $s_1 = s_2 = \cdots = s_k = 0$. Similarly, since φ^{-1} and σ^{-1} are isomorphisms, if B is linearly independent then A is linearly independent. So A is linearly independent if and only if B is. Therefore A is a basis for V_1 if and only if B is a basis for V_2 and so $\dim_{D_1}(V_1) = \dim_{D_2}(V_2)$, as claimed (recall that V_1 and V_2 are finite dimensional, by hypothesis).

Proposition IX.1.17 (continued 7)

Proof (continued). (ii) Suppose there is an isomorphism of rings

$\mathrm{Mat}_{n_1}(D_1) \cong \mathrm{Mat}_{n_2}(D_2)$. By Theorem VII.1.4, $\mathrm{Hom}_{D_1^{\mathrm{op}}}(V_1, V_1) \cong \mathrm{Mat}_{n_1}((D_1^{\mathrm{op}})^{\mathrm{op}})$ and $\mathrm{Hom}_{D_2^{\mathrm{op}}}(V_2, V_2) \cong \mathrm{Mat}_{n_2}((D_2^{\mathrm{op}})^{\mathrm{op}})$. By Exercise III.1.17(d), $(D_1^{\mathrm{op}})^{\mathrm{op}} = D_1$ and $(D_2^{\mathrm{op}})^{\mathrm{op}} = D_2$, so

$$\mathrm{Hom}_{D_1^{\mathrm{op}}}(V_1, V_1) \cong \mathrm{Mat}_{n_1}(D_1) \cong \mathrm{Mat}_{n_2}(D_2) \cong \mathrm{Hom}_{D_2^{\mathrm{op}}}(V_2, V_2).$$

By part (i), $n_1 = \dim_{D_1^{\mathrm{op}}}(V_1, V_1) = \dim_{D_2^{\mathrm{op}}}(V_2, V_2) = n_2$ and $D_1^{\mathrm{op}} \cong D_2^{\mathrm{op}}$. By Exercise III.1.17(e), $D_1 \cong D_2$, as claimed. □