

Ring Theory

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Chapter 1

Vector Spaces and Modules.

1.1 Definitions and Examples

Definition. We call a nonempty set V a **vector space** over a field F , if given a binary operation $+: V \times V \rightarrow V$ called **vector addition** and an operation $\cdot: F \times V \rightarrow V$ called **scalar multiplication**, we have that $(V, +)$ forms an abelian group, and for all $v, w \in V$ and $\alpha, \beta \in F$:

- (1) $\alpha(v + w) = \alpha v + \alpha w$.
- (2) $(\alpha + \beta)v = \alpha v + \beta v$.
- (3) $\alpha(\beta v) = (\alpha\beta)v$.
- (4) $1v = v$, where 1 is the identity element of F under its multiplication.

Lemma 1.1.1. *Let V be a vector space over a field F . Then the operation $\cdot: F \times V \rightarrow V$ of scalar multiplication is a group homomorphism of V into V .*

Proof. Taking $\cdot: F \times V \rightarrow V$ by $(\alpha, v) \rightarrow \alpha v$, restrict \cdot to V , i.e. consider $\cdot|_V: V \rightarrow V$ by $v \rightarrow \alpha v$ for $\alpha \in F$. By (1) of the scalar multiplication rules, we get that $\cdot|_V$ is a homomorphism; which makes \cdot a homomorphism. ■

Example 1.1. (1) Let F be a field and $F \subseteq K$ a field extension of F . Then K is a vector space over F with $+$ the usual addition of K and \cdot the multiplication of K restricted to F by the first part, i.e. the product $\cdot: v \rightarrow \alpha v$ with $\alpha \in F$.

(2) Let F be a field and consider F^n the set of ordered n -tuples of elements of F , for some $n \in \mathbb{Z}^+$. Take $+: (v, w) \rightarrow v + w$ by $(v_1, \dots, v_n) + (w_1, \dots, w_n) = (v_1 + w_1, \dots, v_n + w_n)$, where $v = (v_1, \dots, v_n), w = (w_1, \dots, w_n) \in F^n$, and $\cdot: (\alpha, v) \rightarrow \alpha v$ by $\alpha(v_1, \dots, v_n) = (\alpha v_1, \dots, \alpha v_n)$. Then F^n is a vector space over F .

(3) Let F be any field and let $F[x]$ be the polynomial field over F . Take $+$ to be polynomial addition, and \cdot the multiplication of a constant in F by a polynomial in $F[x]$. Then $F[x]$ is a vector space over F .

- (4) Let $F[x]$ be the polynomial field over a field F and consider the set $P_n = \{f \in F[x] : \deg f < n\}$. Then P_n as a subset of $F[x]$ forms a vector space over F under the same operations $+$ and \cdot (this last example motivates the following definition).

Definition. Let V be a vector space over a field F . We say a subset $W \subseteq V$ is a **subspace** of V if W is also a vector space over F .

Lemma 1.1.2. Let V be a vector space over a field F , and let $W \subseteq V$ be a subspace of V . Then for all $w_1, w_2 \in W$ and $\alpha, \beta \in F$, $\alpha w_1 + \beta w_2 \in W$.

Proof. Since W is a vector space we have that $\alpha w_1, \beta w_2 \in W$; then by closure of vector addition, $\alpha w_1 + \beta w_2 \in W$. ■

Definition. Let U and V be vector spaces over a field F . We call a mapping $T : U \rightarrow V$ a **homomorphism** of U into V if:

- (1) $T(u_1 + u_2) = T(u_1) + T(u_2)$.
- (2) $T(\alpha u_1) = \alpha T(u_1)$.

for all $u_1, u_2 \in U$ and $\alpha \in F$. If T is 1-1 from U onto V , then we call T an **isomorphism** and we say U is **isomorphic** to V and write $U \simeq V$. We define the **kernal** of T to be $\ker T = \{u \in U : T(u) = 0\}$. We call the set of all homomorphisms of U into V $\text{hom}(U, V)$.

Example 1.2. Let F be a field and consider the vector spaces F^n and P_n defined in examples (2) and (4). Then $P_n \simeq F^n$. Take the map $a_0 + a_1x + \cdots + a_nx^{n-1} \rightarrow (a_0, \dots, a_{n-1})$, which defines an isomorphism.

Lemma 1.1.3. If V is a vector space over a field F , then for all $\alpha \in F$ and $v \in V$:

- (1) $\alpha 0 = 0$.
- (2) $0v = 0$.
- (3) $(-\alpha)v = -(\alpha v)$.
- (4) $\alpha v = 0$ and $v \neq 0$ implies $\alpha = 0$.

Proof. (1) $\alpha 0 = \alpha(0 + 0) = \alpha 0 + \alpha 0$, hence $\alpha 0 = 0$.

(2) $0v = (0 + 0)v = 0v + 0v$, hence $0v = 0$.

(3) We have $0 = 0v$, that is $0 = (\alpha + (-\alpha))v = \alpha v + (-\alpha)v$. Adding both sides by $-(\alpha v)$ we get the desired result.

(4) If $\alpha \neq 0$ and $v \neq 0$, then $0 = \alpha^{-1}0 = \alpha^{-1}(\alpha v) = 1v = v$ which makes $v = 0$, which cannot happen. So $\alpha = 0$. ■

Lemma 1.1.4. Let V be a vector space over a field F and let $W \subseteq V$ be a subspace of V . Then V/W is a vector space over F where for $v_1 + W, v_2 + W \in V/W$ and $\alpha \in F$ we have:

$$(1) (v_1 + W) + (v_2 + W) = (v_1 + v_2 + W).$$

$$(2) (v_1 + W) = \alpha v_1 + W.$$

Proof. Since V as an abelian group, and W a subgroup of V under $+$, we get that V/W as the quotient group of V over W ; which as abelian since W as abelian.

Suppose now that for $v, v' \in V$ that $v + W = v' + W$, then for $\alpha \in F$ we have $\alpha(v + W) = \alpha(v' + W)$, and by hypotheses, we have $v - v' \in W$. Now since W as a subspace, $\alpha(v - v') \in W$ as well, so $\alpha v + W = \alpha v' + W$, so the product as well defined.

Now consider $v, v' \in W$ and $\alpha, \beta \in F$. By our product we have that $\alpha(v + w + W) = \alpha(v + w) + W = (\alpha v + \alpha w) + W = (\alpha v + W) + (\alpha v' + W)$, $(\alpha + \beta)(v + W) = (\alpha + \beta)v + W = (\alpha v + \beta v) + W = \alpha(v + W) + \beta(v + W)$, $\alpha(\beta v + W) = \alpha\beta v + W = (\alpha\beta)v + W$, and finally, $1(v + w) = 1v + W = v + W$. Therefore V/W as a vector space over F . ■

Definition. Let V be a vector space over F and let $W \subseteq V$ be a subspace of V . We call the vector space formed by taking the quotient group of V over W , V/W the **quotient space** of V over W .

Theorem 1.1.5 (The First Homomorphism Theorem for Vector Spaces). *If $T : U \rightarrow V$ as a homomorphism of U onto V , and $W = \ker T$, then $V \simeq U/W$. If U as a vector space and $W \subseteq U$ as a subspace of U , then there as a homomorphism of U onto U/W .*

Proof. By the fundamental theorem of homomorphisms, we have that, as groups, $V \simeq U/W$. That there as a homomorphism from U onto U/W follows immediately. ■

Definition. Let V bhe a vector space over a field F and let $\{U_i\}_{i=1}^n$ be a collection of subspaces of V . We call V the **internal direct sum** of $\{U_i\}$ if every element of V can be written uniquely as a vector sum of elements of each U_i for $1 \leq i \leq n$; That as for $v \in V$, $v = u_1 + \dots + u_n$ as unique where $u_i \in U_i$.

Lemma 1.1.6. *Let $\{V_i\}_{i=1}^n$ be a collection of vector spaces over a field F and let $V = \prod_{i=1}^n V_i$ and define $+: V \times V \rightarrow V$ by $(v_1, \dots, v_n) + (v'_1, \dots, v'_n) = (v_1 + v'_1, \dots, v_n + v'_n)$ and define $\cdot: F \times V \rightarrow V$ by $\alpha(v_1, \dots, v_n) = (\alpha v_1, \dots, \alpha v_n)$. Then V as a vector space over F .*

Proof. Since V_i as a vector space for all $1 \leq i \leq n$, they are all abelian groups, hence V as closed under $+$, and inherits associativity, as well a s commutativity. Now letting $0 = (0_1, \dots, 0_n)$, where 0_i as the identity of V_i , we get for any $v \in V$ that $v + 0 = 0 + v = v$, so 0 as the identity. Likewise for any $v \in V$, $-v = (-v_1, \dots, -v_n)$ serves as the inverse for v . So $(V, +)$ forms an abelian group.

Now by the axioms of scalar multiplication on each of the V_i , let $v = (v_1, \dots, v_n), w = (w_1, \dots, w_n) \in V$ and $\alpha, \beta \in F$. We get $\alpha(v + w) = \alpha(v_1 + w_1, \dots, v_n + w_n) = (\alpha(v_1 + w_1), \dots, \alpha(v_n + w_n)) = (\alpha v_1 + \alpha w_1, \dots, \alpha v_n + \alpha w_n) = (\alpha v_1, \dots, \alpha v_n) + (\alpha w_1, \dots, \alpha w_n) = \alpha v + \alpha w$. We also get $(\alpha + \beta)v = ((\alpha + \beta)v_1, \dots, (\alpha + \beta)v_n) = (\alpha v_1 + \beta v_1, \dots, \alpha v_n + \beta v_n) = (\alpha v_1, \dots, \alpha v_n) + (\beta v_1, \dots, \beta v_n) = \alpha v + \beta v$. Through similar calculation, we get that $\alpha(\beta v) = (\alpha\beta)v$ and $1v = v$; which makes V into a vector space. ■

Definition. Let $\{V_i\}_{i=1}^n$ be a collection of vector spaces over a field F and let $V = \prod_{i=1}^n V_i$ and define $+: V \times V \rightarrow V$ by $(v_1, \dots, v_n) + (v'_1, \dots, v'_n) = (v_1 + v'_1, \dots, v_n + v'_n)$ and define $\cdot: F \times V \rightarrow V$ by $\alpha(v_1, \dots, v_n) = (\alpha v_1, \dots, \alpha v_n)$. We call V , as a vector space over F the **external direct sum** of $\{V_i\}$ and write $V = V_1 \oplus \dots \oplus V_n$, or $V = \bigoplus_{i=1}^n V_i$.

Theorem 1.1.7. *Let V be a vector space and let $\{U_i\}_{i=1}^n$ be a collection of subspaces of V . If V is the internal direct sum of $\{U_i\}$ then V is isomorphic to the external direct sum of $\{U_i\}$; that is: $V \simeq \bigoplus_{i=1}^n U_i$.*

Proof. Let $v \in V$. By hypothesis $v = u_1 + \cdots + u_n$ with $u_i \in U_i$ for $1 \leq i \leq n$, and it is a unique representation of v . Define then, the map $T : V \rightarrow \bigoplus_{i=1}^n U_i$ by the map $v = v = u_1 + \cdots + u_n \rightarrow (u_1, \dots, u_n)$. Since v has a unique representation by definition, T is well defined; moreover it is 1-1, as $(u_1, \dots, u_n) = (w_1, \dots, w_n)$ implies $u_i = w_i$ for all $1 \leq i \leq n$, hence $u_1 + \cdots + u_n = w_1 + \cdots + w_n$, and since this sum is unique, they both represent a vector $v \in V$. That T is onto follows directly from definition.

Finally, let $v, w \in V$, then $v = u_1 + \cdots + u_n$ and $w = w_1 + \cdots + w_n$. Hence $T(v + w) = T(u_1 + w_1 + \cdots + u_n + w_n) = (u_1 + w_1, \dots, u_n + w_n) = (u_1, \dots, u_n) + (w_1, \dots, w_n) = T(v) + T(w)$. Similarly, $T(\alpha v) = (\alpha v)$. ■

Remark. That V is the internal direct sum of $\{U_i\}$ and that $V \simeq U_1 \oplus \cdots \oplus U_n$ by the above theorem permits us to write $V = U_1 \oplus \cdots \oplus U_n$, or $V = \bigoplus_{i=1}^n U_i$.

1.2 Linear Independence and Bases.

Definition. If V is a vector space over a field F and give $v_1, \dots, v_n \in V$, then we call any element $v \in V$ of the form $v = \alpha_1 v_1 + \cdots + \alpha_n v_n$ for $\alpha_1, \dots, \alpha_n \in F$ a **linear combination** of v_1, \dots, v_n over F .

Definition. Let V be a vector space. We call the set of all linear combinations of finite sets of elements of a nonempty subset $S \subseteq V$ the **linear span** of S ; and we write $\text{span } S$.

Lemma 1.2.1. *If V is a vector space, and $S \subseteq V$ is nonempty, then $\text{span } S$ is a subspace of V .*

Proof. Since $\text{span } S$ is the set of all linear combinations of finite sets of elements of S , it is clear that $\text{span } S \subseteq V$. Now let $v, w \in \text{span } S$, then $v = \lambda_1 v_1 + \cdots + \lambda_n v_n$ and $w = \mu_1 w_1 + \cdots + \mu_m w_m$; where $\lambda_i, \mu_j \in F$ and $v_i, w_j \in S$ for $1 \leq i \leq n$ and $1 \leq j \leq m$. Now consider $\alpha, \beta \in F$, then $\alpha v + \beta w = \alpha(\lambda_1 v_1 + \cdots + \lambda_n v_n) + \beta(\mu_1 w_1 + \cdots + \mu_m w_m) = (\alpha \lambda_1) v_1 + \cdots + (\alpha \lambda_n) v_n + (\beta \mu_1) w_1 + \cdots + (\beta \mu_m) w_m$ which is a linear combination of the finite set $\{v_1, \dots, v_n, w_1, \dots, w_m\}$ of elements of S . Therefore $\alpha v + \beta w \in \text{span } S$. ■

Lemma 1.2.2. *If $S, T \subseteq V$, then:*

- (1) $S \subseteq T$ implies $\text{span } S \subseteq \text{span } T$.
- (2) $\text{span } (S \cup T) = \text{span } S + \text{span } T$.
- (3) $\text{span } (\text{span } S) = \text{span } S$.

Proof. (1) Let $v \in \text{span } S$, then $v = \lambda_1 v_1 + \cdots + \lambda_n v_n$, with $v_1, \dots, v_n \in S$. Since $S \subseteq T$, $v_1, \dots, v_n \in T$, hence $v \in \text{span } T$.

- (2) Let $v \in \text{span}(S \cup T)$, then $v = \lambda_1 v_1 + \cdots + \lambda_n v_n + \mu_1 w_1 + \cdots + \mu_m w_m = (\lambda_1 v_1 + \cdots + \lambda_n v_n) + (\mu_1 w_1 + \cdots + \mu_m w_m)$, where $v_i \in S$ and $w_j \in T$. Then $v \in \text{span } S + \text{span } T$.

Now for $v \in \text{span } S + \text{span } T$, $v = u + w$ with $u \in \text{span } S$ and $w \in \text{span } T$, hence v is a linear combination of the finite set $\{u_1, \dots, u_n, w_1, \dots, w_n\}$ of elements of $S \cup T$, hence $v \in \text{span}(S \cup T)$.

- (3) Clearly $\text{span } S \in \text{span}(\text{span } S)$. Suppose then that $v \in \text{span}(\text{span } S)$. Then $v = \alpha_1 v_1 + \cdots + \alpha_n v_n$ where $v_i = \beta_{i1} v_{i1} + \cdots + \beta_{im} v_{im}$ where $v_{ij} \in S$. Hence $v = ((\alpha_1 \beta_{11}) v_{11} + \cdots + (\alpha_1 \beta_{1m}) v_{1m}) + \cdots + (\alpha_n \beta_{n1}) v_{n1} + \cdots + (\alpha_n \beta_{nm}) v_{nm}$. Therefore $\text{span}(\text{span } S) \subseteq \text{span } S$. ■

Definition. We call a vector space V over a field F **finite dimensional** over F if there is a finite subset $S \subseteq V$ whose linear span is V ; that is $\text{span } S = V$.

Example 1.3. F^n is finite dimensional. Let $S = \{(1, 0, \dots, 0), (0, 1, \dots, 0), \dots, (0, 0, \dots, 1)\}$. Then $\text{span } S = F^n$.

Definition. Let V be a vector space over a field F . We say that a set of $\{v_1, \dots, v_n\}$ of elements of V **linearly dependent** over F if there exist $\lambda_1, \dots, \lambda_n \in F$, not all 0 such that $\lambda_1 v_1 + \cdots + \lambda_n v_n = 0$. We call $\{v_1, \dots, v_n\}$ **linearly independent** over F if it is not linearly dependent over F ; that is $\lambda_1 v_1 + \cdots + \lambda_n v_n = 0$ implies $\lambda_1 = \cdots = \lambda_n = 0$.

Example 1.4. (1) In F^3 , the vectors $(1, 0, 0)$, $(0, 1, 0)$, $(0, 0, 1)$ are linearly independent, where as $(1, 1, 0)$, $(3, 1, 3)$, $(5, 3, 3)$ are linearly dependent.

- (2) Consider the set \mathbb{C} of complex numbets as a vector space over \mathbb{R} . The vectors $1, i$ are linearly independent over \mathbb{R} since $i \notin \mathbb{R}$. However, $1, i$ is not linearly independent over \mathbb{C} , as $i^2 + 1 = 0$ by definition; where $\lambda_1 = i$ and $\lambda_2 = 1$.

Lemma 1.2.3. If $v_1, \dots, v_n \in V$ are linearly independent, then every element in $\text{span}\{v_1, \dots, v_n\}$ can be represented uniquely as a linear combination of v_1, \dots, v_n .

Proof. Let $v \in \text{span}\{v_1, \dots, v_n\}$ such that $v = \lambda_1 v_1 + \cdots + \lambda_n v_n$ and $v = \mu_1 v_1 + \cdots + \mu_n v_n$. Then $\lambda_1 v_1 + \cdots + \lambda_n v_n = \mu_1 v_1 + \cdots + \mu_n v_n$, then $(\lambda_1 - \mu_1) v_1 + \cdots + (\lambda_n - \mu_n) v_n = 0$. By linear independence, this implies that $\lambda_i - \mu_i = 0$, for all $1 \leq i \leq n$. Therefore v is uniquely represented. ■

Theorem 1.2.4. If $v_1, \dots, v_n \in V$, then they are linearly independent, or v_k is a linear combination of v_1, \dots, v_{k-1} for $1 \leq k \leq n$.

Proof. If v_1, \dots, v_n are linearly independent, then we are done. Now suppose that they are linearly dependent, then $\lambda_1 v_1 + \cdots + \lambda_n v_n = 0$ for $\lambda_1, \dots, \lambda_n$ not all 0. Let k be the largest such integer for which $\lambda_k \neq 0$, and $\lambda_i = 0$ for all $k < i$. Then $\lambda_1 v_1 + \cdots + \lambda_n v_n = \lambda_1 v_1 + \cdots + \lambda_k v_k$ where $\lambda_1, \dots, \lambda_k$ are not all 0 for $1 \leq i \leq k$. Then we have that $v_k = (\lambda_k^{-1} \lambda_1) v_1 + \cdots + (\lambda_k^{-1} \lambda_{k-1}) v_{k-1}$ which is a linear combination of v_1, \dots, v_{k-1} . ■

Corollary. If $v_1, \dots, v_n \in V$ have W as a linear span, and if v_1, \dots, v_k are linearly independent, then there is a linearly independent subset of $\{v_1, \dots, v_n\}$ of the form $\{v_1, \dots, v_k, v_{i_1}, \dots, v_{i_r}\}$ which span W .

Proof. If v_1, \dots, v_n are linearly independent, then we are done. If not, let j be the smallest such integer for which v_j is a linear combination of its predecessors. Since v_1, \dots, v_k are linearly independent, we get $k < j$. Then consider the set $S = \{v_1, \dots, v_n\} \setminus v_j = \{v_1, \dots, v_k, \dots, v_{j-1}, v_{j+1}, \dots, v_n\}$ which has $n - 1$ elements. Clearly, $\text{span } S \subseteq W$.

Now let $w \in W$, then $w = \lambda_1 v_1 + \dots + \lambda_n v_n$. Since v_j is a linear combination of v_1, \dots, v_{j-1} , we get that $w = \lambda'_1 v_1 + \dots + \lambda'_k v_k + \dots + \lambda'_{j-1} v_{j-1} + \lambda_{j+1} v_{j+1} + \dots + \lambda_n v_n$ which makes $W \subseteq \text{span } S$.

Now if we proceed by removing all vectors which are linear combinations of their predecessors, we get a set $\{v_1, \dots, v_k, v_{i_1}, \dots, v_{i_r}\}$ with $\text{span } S$; by the preceding argument, we get again that $W \subseteq \text{span } S$. ■

Corollary. *If V is a finite dimensional vector space, then there is a finite set of linearly independent vectors $\{v_1, \dots, v_n\}$ such that $\text{span } \{v_1, \dots, v_n\} = V$.*

Proof. By definition, since V is finite dimensional, there is a finite set of vectors $\{u_1, \dots, u_m\}$ with linear span V . Then by the previous corollary, there is a subset $\{v_1, \dots, v_n\}$ of linearly independent vectors whose span is also V . ■

Definition. We call a subset S of a vector space V a **basis** if S consists of linearly independent vectors, and $\text{span } S = V$.

What the above corollary states, is that if V is a finite dimensional vector space, and u_1, \dots, u_m (not necessarily independent), $\text{span } V$, then u_1, \dots, u_m contain a basis of V .

Example 1.5. A basis need not be finite. Consider the polynomial field $F[x]$, the set $\{1, x, x^2, \dots, x_n, \dots\}$ forms a basis of $F[x]$. However, the set $\{1, x, x^2, \dots, x^n\}$ span the subspace P_n of $F[x]$.

Lemma 1.2.5. *If V is a finite dimensional vector space, then $V \simeq F^n$ for some $n \in \mathbb{Z}^+$.*

Proof. By lemma 1.2.3 and the above corollary, any $v \in V$ is the unique combination of basis elements v_1, \dots, v_n ; that is $v = \lambda_1 v_1 + \dots + \lambda_n v_n$. Now take the map $v \rightarrow (\lambda_1, \dots, \lambda_n)$ is well defined, 1-1 by linear independence and onto. Hence $V \simeq F^n$. ■

Remark. In fact if $\{v_1, \dots, v_n\}$ is a basis for V , then $|\{v_1, \dots, v_n\}| = n$.

Lemma 1.2.6. *If $v_1, \dots, v_n \in V$ forms a basis, and $w_1, \dots, w_m \in V$ are linearly independent, then $m \leq n$. Moreover, the set $\{v_1, \dots, v_n\}$ is maximally linearly independent.*

Proof. For any arbitrary vector $v \in V$, v is a linear combination of v_1, \dots, v_n by lemma 1.2.3, hence $\{v_1, \dots, v, v\}$ is linearly dependent. This makes $\{v_1, \dots, v_n\}$ maximally independent.

Now $w_m \in V$ is a linear combination of v_1, \dots, v_n ; moreover they span V by theorem 1.2.4, therefore, by the previous corollary there is a subset $\{w_m, v_{i_1}, \dots, v_{i_k}\}$ with $k \leq n - 1$ which is a basis of V .

Repeating by taking $w_{m-1}, w_m, \dots, v_{i_k}$; we get, eventually, a basis $\{w_{m-1}, w_m, \dots, v_{j_1}, \dots, v_{j_s}\}$, with $s \leq n - 1$. Repeating then of the vectors w_2, \dots, w_{m-2} , we get a basis $\{w_2, \dots, w_{m-1}, \dots, v_\alpha\}$. Since w_1, \dots, w_m are linearly independent, w_1 is not a linear combination of the others, hence the basis contains some v . Now the basis above has $m - 1$ w_i 's, at the cost of one $v \in V$, hence $m - 1 \leq n - 1$; thus $m \leq n$. ■

Corollary. Any two bases have the same number of elements.

Proof. Let $\{v_1, \dots, v_n\}$ and $\{w_1, \dots, w_m\}$ be bases with n and m elements respectively. Since they are both linearly independent, by above we get $m \leq n$ and $n \leq m$. Therefore $m = n$. ■

Corollary. $F^n \simeq F^m$ if and only if $n = m$.

Proof. F^n has the basis $\{(1, 0, \dots, 0)_n, \dots, (0, 0, \dots, 1)_n\}$ and F^m has basis $\{(1, 0, \dots, 0)_m, \dots, (0, 0, \dots, 1)_m\}$, and any isomorphism must map a basis to a basis. ■

Corollary. If V is finite dimensional over F , with $V \simeq F^n$ for some unique n , then any basis in V has exactly n elements.

Definition. If V is a finite dimensional vector space over a field F , with a basis $\{v_1, \dots, v_n\}$ of n elements, we call the n **dimension** of V over F and write $\dim_F V = n$ or $\dim V = n$.

Example 1.6. (1) $\dim F^n = n$.

(2) $\dim_F P_n = n$, and $\dim F[x] = \infty$ (since $F[x]$ is infinite dimensional).

(3) $\dim_{\mathbb{R}} \mathbb{C} = 2$.

Corollary. If V and U are finite dimensional vector spaces over a field F , with $\dim_F V = \dim_F U$, then $V \simeq U$.

Proof. $V \simeq F^n$ and $F^n \simeq U$. By transitivity, we get $V \simeq U$. ■

Lemma 1.2.7. If V is a finite dimensional vector space over F and of $u_1, \dots, u_m \in V$ are linearly independent, then there exist $u_{m+1}, \dots, u_{m+r} \in V$ such that $\{u_1, \dots, u_m, u_{m+1}, u_{m+r}\}$ is a basis of V .

Proof. By finite dimensionality, there is a basis v_1, \dots, v_n of V , which span V . Hence $\text{span}\{u_1, \dots, u_m, v_1, \dots, v_n\} = V$, therefore by theorem 1.2.4 there is a subset $\{u_1, \dots, u_m, v_{i_1}, \dots, v_{i_r}\}$ which is a basis of V . Now just map $v_{i_j} \rightarrow u_{m+j}$ for each $1 \leq j \leq r$. ■

Remark. This gives us a method for constructing bases of vector spaces.

Lemma 1.2.8. If V is finite dimensional, and if W is a subspace of V , then W is also finite dimensional. Moreover $\dim W \leq \dim V$ and $\dim V/W = \dim V - \dim W$.

Proof. If $\dim V = n$, then any set of $n+1$ vectors in V is linearly dependent, by maximality, hence so is any set of $n+1$ vectors in W . Then there exists a maximal set of linearly independent elements in W , w_1, \dots, w_m , with $m \leq n$. If $w \in W$, then w_1, \dots, w_m, w are linearly dependent with $\lambda_1 w_1 + \dots + \lambda_m w_m + \lambda w = 0$. Now $\lambda \neq 0$, for that would imply w_1, \dots, w_m, w linearly independent. Hence $w = \mu_1 w_1 + \dots + \mu_m w_m$ where $\mu_i = \lambda^{-1} \lambda_i$. Thus we get $w \in \text{span}\{w_1, \dots, w_m\}$, i.e. $W = \text{span}\{w_1, \dots, w_m\}$, thus w_1, \dots, w_m form a basis of W . Therefore $m = \dim W \leq \dim V = n$.

Now take $V \rightarrow V/W$ by $v_1, \dots, v_r \rightarrow v'_1, \dots, v'_r$. By lemma 1.2.7, if $\{w_1, \dots, w_m\}$ form a basis of W , then there exist v_{m+1}, \dots, v_{m+r} such that $\{w_1, \dots, w_m, v_{m+1}, v_{m+r}\}$ form a basis for V . That is, for any $v \in V$, $v = \lambda_1 w_1 + \dots + \lambda_m w_m + \mu_1 v_1 + \dots + \mu_r v_r$. Then we get that $v' = \mu_1 v'_1 + \dots + \mu_r v'_r$, hence $\text{span}\{v'_1, \dots, v'_r\} = V/W$. Now if $\gamma_1 v'_1 + \dots + \gamma_r v'_r = 0$, then $\gamma_1 v'_1 + \dots + \gamma_r v_r \in W$, making $\gamma_1 v'_1 + \dots + \gamma_r v_r = \lambda_1 w_1 + \dots + \lambda_m w_m$. By linear independence, $\gamma_i, \lambda_j = 0$ for all $1 \leq i \leq r$ and $1 \leq j \leq m$. This V/W has a basis of $r = \dim V - \dim W$ elements. Therefore $\dim V/W = \dim v - \dim W$. ■

Corollary. *If U and W are finite dimensional subspaces of a vector space V , then $U + W$ is finite dimensional, and $\dim(U + W) = \dim U + \dim W - \dim(U \cap W)$.*

Proof. We have $U + W/W \simeq U/U \cap W$. Hence we get that $\dim(U + W)/W = \dim(U/U \cap W) = \dim U - \dim(U \cap W)$. Then $\dim(U + W) = \dim(U + W)/W + \dim W = \dim U - \dim(U \cap W) + \dim W = \dim U + \dim W - \dim(U \cap W)$. ■

1.3 Dual Spaces.

Lemma 1.3.1. *Let V and W be vector spaces over a field F . Then $\text{hom}(V, W)$ is a vector space over F .*

Proof. First, let $T, L \in \text{hom}(V, W)$, and $\alpha, \beta \in F$. Then $T + L(\alpha v + \beta u) = \alpha T(v) + \beta T(u) + \alpha L(v) + \beta L(u) = \alpha(T + L)(v) + \beta(T + L)(u)$, so $T + L \in \text{hom}(V, W)$. Since $+$ is just function addition, it is associative. Likewise, the zero map $0 : V \rightarrow W$ by $v \rightarrow 0$ and the map $-T : V \rightarrow W$ by $v \rightarrow -T(v)$ define the identity of $\text{hom}(V, W)$ and the inverse of T respectively. This makes $(\text{hom}(V, W), +)$ into a group. Now by the properties of homomorphisms, we also see that $\alpha(T + L) = \alpha T + \alpha L$, $(\alpha + \beta)T = \alpha T + \beta T$, $\alpha(\beta T) = (\alpha\beta)T$ and $T(1v) = 1T(v)$. This makes $\text{hom}(V, W)$ a vector space. ■

Lemma 1.3.2. *If $S, T \in \text{hom}(V, W)$ such that $S(v_i) = T(v_i)$ for all v_i in a basis $\{v_1, \dots, v_n\}$ of V , then $S = T$.*

Proof. Since $\{v_1, \dots, v_n\}$ is a basis of V , we have for every $v \in V$, $v = \lambda_1 v_1 + \dots + \lambda_n v_n$ for unique $\lambda_1, \dots, \lambda_n \in F$. Then we get $S(v) = \lambda_1 S(v_1) + \dots + \lambda_n S(v_n) = \lambda_1 T(v_1) + \dots + \lambda_n T(v_n) = T(v)$. Thus $S(v) = T(v)$ for all $v \in V$. ■

Theorem 1.3.3. *If V and W are vector spaces with $\dim V = m$ and $\dim W = n$, then $\dim \text{hom}(V, W) = mn$.*

Proof. Let $\{v_1, \dots, v_m\}$ and $\{w_1, \dots, w_n\}$ be bases for V and W , respectively. Then for any $v \in V$, $v = \lambda_1 v_1 + \dots + \lambda_m v_m$ for unique $\lambda_1, \dots, \lambda_m \in F$. Now let $T_{ij} \in \text{hom}(V, W)$ be defined such that $T_{ij}(v_i) = 0$ for $i \neq j$ and $T_{ij}(v_j) = w_j$; for $1 \leq i \leq m$ and $1 \leq j \leq n$. We see there are mn possible such T_{ij} . Now let $S \in \text{hom}(V, W)$, then $S(v_i) \in W$, hence $S = \mu_{11}w_1 + \dots + \mu_{1n}w_n$ for unique $\mu_{11}, \dots, \mu_{1n} \in F$. Then $S(v_i) = \mu_{i1}w_1 + \dots + \mu_{in}w_n$ for unique $\mu_{i1}, \dots, \mu_{in} \in F$. Now let $S_0 = \mu_{11}T_{11} + \dots + \mu_{1n}T_{1n} + \dots + \mu_{m1}T_{m1} + \dots + \mu_{mn}T_{mn}$. Then $S_0(v_k) = (\mu_{11}T_{11} + \dots + \mu_{1n}T_{1n} + \dots + \mu_{m1}T_{m1} + \dots + \mu_{mn}T_{mn})(v_k) = \mu_{11}T_{11}(v_k) + \dots + \mu_{1n}T_{1n}(v_k) + \dots + \mu_{m1}T_{m1}(v_k) + \dots + \mu_{mn}T_{mn}(v_k)$. Since $T_{ij}(v_k) = 0$ for $i \neq k$ we get $S_0(v_k) = \mu_{k1}w_1 + \dots + \mu_{kn}w_n$. So $S_0(v_k) = S(v_k)$ for the basis $\{v_1, \dots, v_m\}$ of V ; this makes $S_0 = S$.

Now since $S = S_0$ is arbitrary, and subsequently a linear combination of the T_{ij} , we get that $\text{span}\{T_{11}, \dots, T_{1n}, \dots, T_{m1}, \dots, T_{mn}\} = \text{hom}(V, W)$. Now suppose for $\beta_{11}, \dots, \beta_{1n}, \dots, \beta_{m1}, \dots, \beta_{mn} \in F$ that $\beta_{11}T_{11} + \dots + \beta_{1n}T_{1n} + \dots + \beta_{m1}T_{m1} + \dots + \beta_{mn}T_{mn} = 0$. Then we get that $(\beta_{11}T_{11} + \dots + \beta_{1n}T_{1n} + \dots + \beta_{m1}T_{m1} + \dots + \beta_{mn}T_{mn})(v_k) = \beta_{k1}w_1 + \dots + \beta_{kn}w_n = 0$. Since $\{w_1, \dots, w_n\}$ is a basis of W , this makes $\beta_{kj} = 0$ for all $1 \leq k \leq m$. Thus $\{T_{11}, \dots, T_{1n}, \dots, T_{m1}, \dots, T_{mn}\}$ linearly independent, and hence a basis of $\text{hom}(V, W)$. Therefore, $\dim \text{hom}(V, W) = mn$. ■

Corollary. $\dim \text{hom}(V, V) = m^2$.

Corollary. $\dim \text{hom}(V, F) = m$.

Definition. Let V be a vector space over a field F . We call the vector space $\text{hom}(V, F)$ the **dual space** of V and denote it $\text{dual } V$. We call elements of $\text{dual } V$ **linear functionals** on V into F .

If V is an infinite dimensional vector space, the dual V is very big and of no interest. In these cases, we use properties of other possible structures of $\text{dual } V$ to find a restricted subspace. If V is finite dimensional, then $\text{dual } V$ is finite and always defined.

Lemma 1.3.4. *If V is a finite dimensional vector space, and $v \neq 0 \in V$, then there is a linear functional $\hat{v} \in \text{dual } V$ such that $\hat{v}(v) \neq 0$.*

Proof. Let $\{v_1, \dots, v_n\}$ be a bases of V and let $\hat{v}_i \in \text{dual } V$ be defined by $\hat{v}_i(v_j) = 0$ whenever $i \neq j$ and $\hat{v}_i(v_j) = 1$ otherwise. Then if $v = \lambda_1 v_1 + \dots + \lambda_n v_n$, $\hat{v}_i(v) = \lambda_i$. Then $\{\hat{v}_1, \dots, \hat{v}_n\}$ forms a basis of $\text{dual } V$. Now if $v \neq 0 \in V$, by lemma 1.2.7, we get a basis $v_1 = v, v_2, \dots, v_n$. Thence there is a linear functional $\hat{v}_1(v_1) = \hat{v}_1(v) = 1$. ■

Definition. Let V be a finite dimensional vector space with basis $\{v_1, \dots, v_n\}$. We define the **dual basis** of $\{v_1, \dots, v_n\}$ to be a basis of linear functionals $\{\hat{v}_1, \dots, \hat{v}_n\}$ of $\text{dual } V$ such that $\hat{v}_i(v_j) = 0$ wheberver $i \neq j$ and $\hat{v}_i(v_i) = 1$ otherwise.

Lemma 1.3.5. *If V is a finite dimensional vector space, and $T \in \text{dual } V$ such that $T(v)$ is fixed, then the map $\psi : v \rightarrow T_v$, where $T_v(T) = T(v)$ defines an isomorphism of V onto $\text{dual}(\text{dual } V)$.*

Proof. Let $v_0 \in V$. Let $T \in \text{dual } V$ be a linear functional such that $T(v_0)$ is fixed. Then $T(v_0)$ defines a linear functional of $\text{dual } V$ into F . Let $T_{v_0} : \text{dual } V \rightarrow F$ be defined by $T_{v_0}(T) = T(v_0)$, for any $T \in \text{dual } V$. Notice that for $T, L \in \text{dual } V$ and $\alpha, \beta \in F$, we have $T_{v_0}(\alpha T + \beta L) = \alpha T(v_0) + \beta L(v_0) = \alpha T_{v_0}(T) + \beta T_{v_0}(L)$, which makes $T_{v_0} \in \text{dual}(\text{dual } V)$.

Now given any $v \in V$, we can associate it with a $T_v \in \text{dual}(\text{dual } V)$. Now define $\psi : V \rightarrow \text{dual}(\text{dual } V)$ by $\psi : v \rightarrow T_v$. Then for $v, w \in V$ and $\alpha, \beta \in F$ we have $T_{\alpha v + \beta w}(T) = \alpha T(v) + \beta T(w) = \alpha T_v(T) + \beta T_w(T)$, so ψ is a homomorphism of V onto $\text{dual}(\text{dual } V)$; ψ is onto by definition.

Now let $v \in \ker \psi$. So $\psi(v) = 0$; that means $t_v(T) = T(v) = 0$ for all $T \in \text{dual } V$. However, by lemma 1.3.3, there must be a $T \in \text{dual } V$ for which $T(v) \neq 0$ when $v \neq 0$. Therefore, if $v \in \ker T$, it must be that $v = 0$, that is $\ker T = (0)$. Thus ψ is 1-1, which makes it an isomorphism. ■

Definition. Let W be a subspace of a vector space V . We denote the **annihilator** of W to be $A(W) = \{T \in \text{dual } V : T(v) = 0\}$.

Example 1.7. (1) Let $W_1, W_2 \subseteq V$ be subspaces of a finite dimensional vector space. Let $T \in A(W_1 + W_2)$. Then $T(w) = 0$ for $w \in W_1 + W_2$, hence $w = w_1 + w_2$ where $w_i \in W_i$ for $1 \leq i \leq 2$. So we get $T(w_1) + T(w_2) = 0$ which makes either both $T(w_1), T(w_2)$ 0 or inverses of each other. IN either case, $T(w_1) + T(w_2) \in A(W_1) + A(W_2)$ or $T(w_1) + T(w_2) \in A(W_1) \cap A(W_2) \subseteq A(W_1) + A(W_2)$. So $A(W_1 + W_2) \subseteq A(W_1) + A(W_2)$. On the other hand we have $A(W_1), A(W_2) \subseteq A(W_1 + W_2)$, hence $A(W_1) + A(W_2) \subseteq A(W_1 + W_2)$. Hence we have $A(W_1 + W_2) = A(W_1) + A(W_2)$.

- (2) Similarly, if $T \in A(W_1 \cap W_2)$, then $T(w) = 0$ for $w \in W_1 \cap W_2$, making $T(w) \in A(W_1) \cap A(W_2)$. By similar reasoning to before, we also get that $A(W_1) \cap A(W_2) \subseteq A(W_1 \cap W_2)$. So we get $A(W_1 \cap W_2) = A(W_1) \cap A(W_2)$

Let $\tilde{T} \in \text{dual } W$ such that $\tilde{T}(w) = T(w)$ for any $w \in W$; where $T \in \text{dual } V$. Now define the map $\psi : \text{dual } V \rightarrow \text{dual } W$ by $\psi : T \rightarrow \tilde{T}$. Then we see that $A(W) = \ker \psi$, which makes it a subspace.

Lemma 1.3.6. *If $S \subseteq V$ is a subset of a finite dimensional vector space, then $A(S) \subseteq A(\text{span } S)$.*

Proof. Since $S \subseteq \text{span } S$, it is clear that $A(S) \subseteq A(\text{span } S)$. Now let $v \in \text{span } S$. Then $v = \lambda_1 v_1 + \cdots + \lambda_n v_n$ where $v_1, \dots, v_n \in S$. Let $\psi : \text{dual } V \rightarrow \text{dual } S$ by $T \rightarrow \tilde{T}$ where $\tilde{T}(s) = T(s)$ for all $s \in S$. Then $\psi(v) = \lambda_1 \psi(v_1) + \cdots + \lambda_n \psi(v_n) = \psi(v) = \lambda_1 T(v_1) + \cdots + \lambda_n T(v_n)$. Since $\ker \psi = A(S)$, and $T(v_i) = 0$ for all $v_i \in S$ for $1 \leq i \leq n$, we get $\psi(v) = 0$ hence $v \in A(S)$; which puts $A(\text{span } S) \subseteq A(S)$. ■

Theorem 1.3.7 (The Second Homomorphism Theorem for Vector Spaces). *If V is a finite dimensional vector space, and $W \subseteq V$ is a subspace of V , then $\text{dual } W \simeq \text{dual } V / A(W)$, and $\dim A(W) = \dim V - \dim W$.*

Proof. Consider again the map $\psi : \text{dual } V \rightarrow \text{dual } W$ by $T \rightarrow \tilde{T}$, where $\tilde{T}(w) = T(w)$ for all $w \in W$; and recalling above that $A(W) = \ker T$.

Let $h \in \text{dual } W$. By lemma 1.2.7, if $\{w_1, \dots, w_m\}$ is a basis of W , then there is a basis $\{w_1, \dots, w_m, v_1, \dots, v_r\}$; hence $\dim V = r + m$. Let W_1 be a subspace of V such that $\text{Span}\{v_1, \dots, v_r\} = W_1$. Then $V = W \oplus W_1$. Now if $h \in \text{dual } W$, let $f \in \text{dual } V$ be defined by $f(v) = w$ where $v = w + w_1 \in W \oplus W_1$. By definition, we have that $f \in \text{dual } V$ and $f = h$. So $\psi(f) = h$ making ψ onto. Since $A(W) = \ker \psi$, by the first homomorphism theorem for vector spaces, we get $\text{dual } W \simeq \text{dual } V / A(W)$.

Moreover, we get $\dim \text{dual } W = \dim \text{dual } V / A(W) = \dim \text{dual } V - \dim A(W)$, and since $\dim \text{dual } V = \dim V$ and $\dim \text{dual } W = \dim W$; we get $\dim A(W) = \dim V - \dim W$. ■

Corollary. $A(A(W)) = W$.

Proof. Notice that $A(A(W)) \subseteq \text{dual}(\text{dual } V)$. Clearly, $W \subseteq A(A(W))$, for if $\psi(w) = T_w$ by $T_w(f) = f(w)$ and $T_w = 0$ for all $f \in A(W)$. Now by above we get $\dim A(A(W)) = \dim \text{dual } V - \dim A(W) = \dim V - (\dim V - \dim W) = \dim W$. This makes $W \simeq A(A(W))$; and since $W \subseteq A(A(W))$, we get $W = A(A(W))$. ■

Theorem 1.3.8. *The system of homogeneous linear equations:*

$$\begin{aligned} a_{11}x_1 + \cdots + a_{1n}x_n &= 0 \\ &\vdots \\ a_{m1}x_1 + \cdots + a_{mn}x_n &= 0 \end{aligned} \tag{1.1}$$

where $a_{ij} \in F$ is of rank r , then there are $n - r$ linearly independent solutions in F^n .

Proof. Consider the system described by equation 1.1, with $a_{ij} \in F$ for $1 \leq i \leq m$ and $1 \leq j \leq n$. Let U be a subspace of m vectors generated by $\{(a_{11}, \dots, a_{1n}), \dots, (a_{m1}, \dots, a_{mn})\}$. Consider the basis $\{(1, 0, \dots, 0), \dots, (0, 0, \dots, 1)\}$ of F^n and let $\{\hat{v}_1, \dots, \hat{v}_n\}$ be its dual basis. Then $T \in \text{dual } F^n$ has the form $T = x_1 \hat{v}_1 + \dots + x_n \hat{v}_n$, with $x_i \in F$ for $1 \leq i \leq n$.

Now for $(a_{11}, \dots, a_{1n}) \in U$, $T(a_{11}, \dots, a_{1n}) = (x_1 \hat{v}_1 + \dots + x_n \hat{v}_n)(a_{11}, \dots, a_{1n}) = a_{11}x_1 + \dots + a_{1n}x_n$, since $\hat{v}_i(v_j) = 0$ for $i \neq j$. Conversely, every solution (x_1, \dots, x_n) gives an element of the form $x_1 \hat{v}_1 + \dots + x_n \hat{v}_n$ in $A(U)$. Therefore, the number of linearly independent solutions of equation 1.1 is $\dim A(U) = \dim V - \dim U = n - r$. ■

Corollary. *If $n > m$, then there is a solution (x_1, \dots, x_n) where not all x_i is 0.*

1.4 Inner Product Spaces.