# Lecture 6 - UM 102 (Spring 2021) 

Vamsi Pritham Pingali

IISc

## Recap

- Defined orthogonal complements and


## Recap

- Defined orthogonal complements and proved the orthogonal decomposition theorem.


## Recap

- Defined orthogonal complements and proved the orthogonal decomposition theorem.
- Stated and
- Defined orthogonal complements and proved the orthogonal decomposition theorem.
- Stated and solved the approximation problem.
- Defined orthogonal complements and proved the orthogonal decomposition theorem.
- Stated and solved the approximation problem.
- Gave three examples
- Defined orthogonal complements and proved the orthogonal decomposition theorem.
- Stated and solved the approximation problem.
- Gave three examples of applications of
- Defined orthogonal complements and proved the orthogonal decomposition theorem.
- Stated and solved the approximation problem.
- Gave three examples of applications of the approximation problem
- Defined orthogonal complements and proved the orthogonal decomposition theorem.
- Stated and solved the approximation problem.
- Gave three examples of applications of the approximation problem (including least squares


## Recap

- Defined orthogonal complements and proved the orthogonal decomposition theorem.
- Stated and solved the approximation problem.
- Gave three examples of applications of the approximation problem (including least squares (which is optional, don't worry too much about it)).


## Inverses

## Inverses

- Recall that our aim
- Recall that our aim was to solve linear equations.
- Recall that our aim was to solve linear equations. In other words, we wanted to
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e.,
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$.
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse $R: W \rightarrow V$ satisfies $T(R(x))=x$, i.e.,
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse $R: W \rightarrow V$ satisfies $T(R(x))=x$, i.e., $T R=I_{W}$.
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse $R: W \rightarrow V$ satisfies $T(R(x))=x$, i.e., $T R=I_{W}$.
- These are not mindless definitions.
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse $R: W \rightarrow V$ satisfies $T(R(x))=x$, i.e., $T R=I_{W}$.
- These are not mindless definitions. For instance, consider
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse $R: W \rightarrow V$ satisfies $T(R(x))=x$, i.e., $T R=I_{W}$.
- These are not mindless definitions. For instance, consider $V=\{1,2\}$ and
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse $R: W \rightarrow V$ satisfies $T(R(x))=x$, i.e., $T R=I_{W}$.
- These are not mindless definitions. For instance, consider $V=\{1,2\}$ and $W=\{0\}$.
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse $R: W \rightarrow V$ satisfies $T(R(x))=x$, i.e., $T R=I_{W}$.
- These are not mindless definitions. For instance, consider $V=\{1,2\}$ and $W=\{0\}$. Define $T: V \rightarrow W$ as $T(1)=T(2)=0$.
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse $R: W \rightarrow V$ satisfies $T(R(x))=x$, i.e., $T R=I_{W}$.
- These are not mindless definitions. For instance, consider $V=\{1,2\}$ and $W=\{0\}$. Define $T: V \rightarrow W$ as $T(1)=T(2)=0$. So define $R_{1}, R_{2}: W \rightarrow V$ as $R_{1}(0)=1$ and
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse $R: W \rightarrow V$ satisfies $T(R(x))=x$, i.e., $T R=I_{W}$.
- These are not mindless definitions. For instance, consider $V=\{1,2\}$ and $W=\{0\}$. Define $T: V \rightarrow W$ as $T(1)=T(2)=0$. So define $R_{1}, R_{2}: W \rightarrow V$ as $R_{1}(0)=1$ and $R_{2}(0)=2$.
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse $R: W \rightarrow V$ satisfies $T(R(x))=x$, i.e., $T R=I_{W}$.
- These are not mindless definitions. For instance, consider $V=\{1,2\}$ and $W=\{0\}$. Define $T: V \rightarrow W$ as $T(1)=T(2)=0$. So define $R_{1}, R_{2}: W \rightarrow V$ as $R_{1}(0)=1$ and $R_{2}(0)=2$. These are right inverses.
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse $R: W \rightarrow V$ satisfies $T(R(x))=x$, i.e., $T R=I_{W}$.
- These are not mindless definitions. For instance, consider $V=\{1,2\}$ and $W=\{0\}$. Define $T: V \rightarrow W$ as $T(1)=T(2)=0$. So define $R_{1}, R_{2}: W \rightarrow V$ as $R_{1}(0)=1$ and $R_{2}(0)=2$. These are right inverses. However, if $L(T(1))=1$, then $L(0)=1$.
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse $R: W \rightarrow V$ satisfies $T(R(x))=x$, i.e., $T R=I_{W}$.
- These are not mindless definitions. For instance, consider $V=\{1,2\}$ and $W=\{0\}$. Define $T: V \rightarrow W$ as $T(1)=T(2)=0$. So define $R_{1}, R_{2}: W \rightarrow V$ as $R_{1}(0)=1$ and $R_{2}(0)=2$. These are right inverses. However, if $L(T(1))=1$, then $L(0)=1$. That means $L(T(2))=1$.
- Recall that our aim was to solve linear equations. In other words, we wanted to solve an inverse problem.
- We shall study some generalities about inverse functions, and then specialise to inverses of linear maps.
- Given two sets $V, W$ and a onto function $T: V \rightarrow W$ A left inverse $L: W \rightarrow V$ is one that satisfies $L(T(x))=x$, i.e., $L T=I_{V}$. A right inverse $R: W \rightarrow V$ satisfies $T(R(x))=x$, i.e., $T R=I_{W}$.
- These are not mindless definitions. For instance, consider $V=\{1,2\}$ and $W=\{0\}$. Define $T: V \rightarrow W$ as $T(1)=T(2)=0$. So define $R_{1}, R_{2}: W \rightarrow V$ as $R_{1}(0)=1$ and $R_{2}(0)=2$. These are right inverses. However, if $L(T(1))=1$, then $L(0)=1$. That means $L(T(2))=1$. Hence there is no left inverse in this example.


## Inverses

## Inverses

- Every onto function $f: V \rightarrow W$


## Inverses

- Every onto function $f: V \rightarrow W$ has at least one right inverse.
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$.
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$.
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$.
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.


## Inverses

- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse.
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses.
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses. If $w=T(v)$,
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses. If $w=T(v)$, then $L_{1}(w)=v=L_{2}(w)$.
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses. If $w=T(v)$, then $L_{1}(w)=v=L_{2}(w)$. Hence $L_{1}=L_{2}($
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses. If $w=T(v)$, then $L_{1}(w)=v=L_{2}(w)$. Hence $L_{1}=L_{2}$ (the onto assumption plays a role).
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses. If $w=T(v)$, then $L_{1}(w)=v=L_{2}(w)$. Hence $L_{1}=L_{2}$ (the onto assumption plays a role).
$T(L(w))=T(L(T(v)))=T(v)=w$.
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses. If $w=T(v)$, then $L_{1}(w)=v=L_{2}(w)$. Hence $L_{1}=L_{2}$ (the onto assumption plays a role).
$T(L(w))=T(L(T(v)))=T(v)=w$. Hence $L$ is also a right inverse.
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses. If $w=T(v)$, then $L_{1}(w)=v=L_{2}(w)$. Hence $L_{1}=L_{2}$ (the onto assumption plays a role).
$T(L(w))=T(L(T(v)))=T(v)=w$. Hence $L$ is also a right inverse.
- Moreover,
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses. If $w=T(v)$, then $L_{1}(w)=v=L_{2}(w)$. Hence $L_{1}=L_{2}$ (the onto assumption plays a role).
$T(L(w))=T(L(T(v)))=T(v)=w$. Hence $L$ is also a right inverse.
- Moreover, if a left inverse exists,
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses. If $w=T(v)$, then $L_{1}(w)=v=L_{2}(w)$. Hence $L_{1}=L_{2}$ (the onto assumption plays a role).
$T(L(w))=T(L(T(v)))=T(v)=w$. Hence $L$ is also a right inverse.
- Moreover, if a left inverse exists, the right inverse is THE left inverse, i.e.,
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses. If $w=T(v)$, then $L_{1}(w)=v=L_{2}(w)$. Hence $L_{1}=L_{2}$ (the onto assumption plays a role).
$T(L(w))=T(L(T(v)))=T(v)=w$. Hence $L$ is also a right inverse.
- Moreover, if a left inverse exists, the right inverse is THE left inverse, i.e., the right inverse is unique. (
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses. If $w=T(v)$, then $L_{1}(w)=v=L_{2}(w)$. Hence $L_{1}=L_{2}$ (the onto assumption plays a role).
$T(L(w))=T(L(T(v)))=T(v)=w$. Hence $L$ is also a right inverse.
- Moreover, if a left inverse exists, the right inverse is THE left inverse, i.e., the right inverse is unique. (Indeed,
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses. If $w=T(v)$, then $L_{1}(w)=v=L_{2}(w)$. Hence $L_{1}=L_{2}$ (the onto assumption plays a role).
$T(L(w))=T(L(T(v)))=T(v)=w$. Hence $L$ is also a right inverse.
- Moreover, if a left inverse exists, the right inverse is THE left inverse, i.e., the right inverse is unique. (Indeed, $T R_{1}=T R_{2}=I$ and hence
- Every onto function $f: V \rightarrow W$ has at least one right inverse. Indeed, for every $w \in W$ there is some $v \in V$ so that $f(v)=w$. Define $R(w)=v$. Clearly $f(R(w))=f(v)=w$. In general, right inverses are not unique.
- Here is an interesting result about left inverses: An onto function $T: V \rightarrow W$ can have at most one left inverse. If $L$ is a left inverse of $T$ then it is also a right inverse!
- Proof: Suppose $L_{1}, L_{2}: W \rightarrow V$ are left inverses. If $w=T(v)$, then $L_{1}(w)=v=L_{2}(w)$. Hence $L_{1}=L_{2}$ (the onto assumption plays a role).
$T(L(w))=T(L(T(v)))=T(v)=w$. Hence $L$ is also a right inverse.
- Moreover, if a left inverse exists, the right inverse is THE left inverse, i.e., the right inverse is unique. (Indeed, $T R_{1}=T R_{2}=I$ and hence $L T R_{1}=L T R_{2} \Rightarrow R_{1}=R_{2}$.


## Inverses

- An onto function $T: V \rightarrow W$ has a
- An onto function $T: V \rightarrow W$ has a left inverse
- An onto function $T: V \rightarrow W$ has a left inverse if and only if
- An onto function $T: V \rightarrow W$ has a left inverse if and only if it is $1-1$ (HW).
- An onto function $T: V \rightarrow W$ has a left inverse if and only if it is $1-1$ (HW).
- A one-onto onto function
- An onto function $T: V \rightarrow W$ has a left inverse if and only if it is $1-1$ (HW).
- A one-onto onto function has a unique left inverse (
- An onto function $T: V \rightarrow W$ has a left inverse if and only if it is $1-1$ (HW).
- A one-onto onto function has a unique left inverse (which we know is also a right inverse).
- An onto function $T: V \rightarrow W$ has a left inverse if and only if it is $1-1$ (HW).
- A one-onto onto function has a unique left inverse (which we know is also a right inverse). Such a $T$ is called invertible and its
- An onto function $T: V \rightarrow W$ has a left inverse if and only if it is $1-1$ (HW).
- A one-onto onto function has a unique left inverse (which we know is also a right inverse). Such a $T$ is called invertible and its (left or right) inverse is denoted as $T^{-1}$.


## Inverses of linear maps

## Inverses of linear maps

- Let $V, W$ be vector spaces


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field.


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map.


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V$,


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.
- Proof: We prove that


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.
- Proof: We prove that $a \Rightarrow b \Rightarrow c \Rightarrow a$.


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.
- Proof: We prove that $a \Rightarrow b \Rightarrow c \Rightarrow a$.
- $a \Rightarrow b$ : We already know that $T^{-1}$ exists.


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.
- Proof: We prove that $a \Rightarrow b \Rightarrow c \Rightarrow a$.
- $a \Rightarrow b$ : We already know that $T^{-1}$ exists. Let $T^{-1}(a v+b w)=c$.


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.
- Proof: We prove that $a \Rightarrow b \Rightarrow c \Rightarrow a$.
- $a \Rightarrow b$ : We already know that $T^{-1}$ exists. Let $T^{-1}(a v+b w)=c$. So $T(c)=a v+b w$ which is


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.
- Proof: We prove that $a \Rightarrow b \Rightarrow c \Rightarrow a$.
- $a \Rightarrow b$ : We already know that $T^{-1}$ exists. Let $T^{-1}(a v+b w)=c$. So $T(c)=a v+b w$ which is $T(c)=a T\left(T^{-1} v\right)+b T\left(T^{-1} w\right)=T\left(a T^{-1} v+b T^{-1} w\right)$.


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.
- Proof: We prove that $a \Rightarrow b \Rightarrow c \Rightarrow a$.
- $a \Rightarrow b$ : We already know that $T^{-1}$ exists. Let $T^{-1}(a v+b w)=c$. So $T(c)=a v+b w$ which is $T(c)=a T\left(T^{-1} v\right)+b T\left(T^{-1} w\right)=T\left(a T^{-1} v+b T^{-1} w\right)$. Since $T$ is $1-1$,


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.
- Proof: We prove that $a \Rightarrow b \Rightarrow c \Rightarrow a$.
- $a \Rightarrow b$ : We already know that $T^{-1}$ exists. Let $T^{-1}(a v+b w)=c$. So $T(c)=a v+b w$ which is $T(c)=a T\left(T^{-1} v\right)+b T\left(T^{-1} w\right)=T\left(a T^{-1} v+b T^{-1} w\right)$. Since $T$ is $1-1, c=a T^{-1} v+b T^{-1} w$.


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.
- Proof: We prove that $a \Rightarrow b \Rightarrow c \Rightarrow a$.
- $a \Rightarrow b$ : We already know that $T^{-1}$ exists. Let $T^{-1}(a v+b w)=c$. So $T(c)=a v+b w$ which is $T(c)=a T\left(T^{-1} v\right)+b T\left(T^{-1} w\right)=T\left(a T^{-1} v+b T^{-1} w\right)$.
Since $T$ is $1-1, c=a T^{-1} v+b T^{-1} w$.
- $b \Rightarrow c$ : If $T(x)=0$, then


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.
- Proof: We prove that $a \Rightarrow b \Rightarrow c \Rightarrow a$.
- $a \Rightarrow b$ : We already know that $T^{-1}$ exists. Let $T^{-1}(a v+b w)=c$. So $T(c)=a v+b w$ which is $T(c)=a T\left(T^{-1} v\right)+b T\left(T^{-1} w\right)=T\left(a T^{-1} v+b T^{-1} w\right)$.
Since $T$ is $1-1, c=a T^{-1} v+b T^{-1} w$.
- $b \Rightarrow c$ : If $T(x)=0$, then $x=T^{-1} T(x)=0$.


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.
- Proof: We prove that $a \Rightarrow b \Rightarrow c \Rightarrow a$.
- $a \Rightarrow b$ : We already know that $T^{-1}$ exists. Let $T^{-1}(a v+b w)=c$. So $T(c)=a v+b w$ which is $T(c)=a T\left(T^{-1} v\right)+b T\left(T^{-1} w\right)=T\left(a T^{-1} v+b T^{-1} w\right)$.
Since $T$ is $1-1, c=a T^{-1} v+b T^{-1} w$.
- $b \Rightarrow c$ : If $T(x)=0$, then $x=T^{-1} T(x)=0$.
- $c \Rightarrow a$ : If $T(v)=T(w)$,


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.
- Proof: We prove that $a \Rightarrow b \Rightarrow c \Rightarrow a$.
- $a \Rightarrow b$ : We already know that $T^{-1}$ exists. Let $T^{-1}(a v+b w)=c$. So $T(c)=a v+b w$ which is $T(c)=a T\left(T^{-1} v\right)+b T\left(T^{-1} w\right)=T\left(a T^{-1} v+b T^{-1} w\right)$.
Since $T$ is $1-1, c=a T^{-1} v+b T^{-1} w$.
- $b \Rightarrow c$ : If $T(x)=0$, then $x=T^{-1} T(x)=0$.
- $c \Rightarrow a$ : If $T(v)=T(w), T(v-w)=0$ and


## Inverses of linear maps

- Let $V, W$ be vector spaces over the same field. Let $T: V \rightarrow W$ be an onto linear map. Then TFAE.
- $T$ is $1-1$.
- $T$ is invertible and the inverse $T^{-1}$ is linear.
- $\forall x \in V, T(x)=0$ if and only if $x=0$.
- Proof: We prove that $a \Rightarrow b \Rightarrow c \Rightarrow a$.
- $a \Rightarrow b$ : We already know that $T^{-1}$ exists. Let $T^{-1}(a v+b w)=c$. So $T(c)=a v+b w$ which is $T(c)=a T\left(T^{-1} v\right)+b T\left(T^{-1} w\right)=T\left(a T^{-1} v+b T^{-1} w\right)$.
Since $T$ is $1-1, c=a T^{-1} v+b T^{-1} w$.
- $b \Rightarrow c$ : If $T(x)=0$, then $x=T^{-1} T(x)=0$.
- $c \Rightarrow a$ : If $T(v)=T(w), T(v-w)=0$ and hence $v=w$.


## In finite dimensions

## In finite dimensions

- Let $V$ be f.d with


## In finite dimensions

- Let $V$ be f.d with $\operatorname{dim}(V)=n$ and


## In finite dimensions

- Let $V$ be f.d with $\operatorname{dim}(V)=n$ and $T: V \rightarrow W$ is an onto linear map. Then TFAE (HW):


## In finite dimensions

- Let $V$ be f.d with $\operatorname{dim}(V)=n$ and $T: V \rightarrow W$ is an onto linear map. Then TFAE (HW):
- $T$ is $1-1$.


## In finite dimensions

- Let $V$ be f.d with $\operatorname{dim}(V)=n$ and $T: V \rightarrow W$ is an onto linear map. Then TFAE (HW):
- $T$ is $1-1$.
- If $e_{1}, \ldots, e_{p}$ are linearly independent in $V$,


## In finite dimensions

- Let $V$ be f.d with $\operatorname{dim}(V)=n$ and $T: V \rightarrow W$ is an onto linear map. Then TFAE (HW):
- $T$ is $1-1$.
- If $e_{1}, \ldots, e_{p}$ are linearly independent in $V$, then $T\left(e_{1}\right), \ldots, T\left(e_{p}\right)$ are so in $W$.


## In finite dimensions

- Let $V$ be f.d with $\operatorname{dim}(V)=n$ and $T: V \rightarrow W$ is an onto linear map. Then TFAE (HW):
- $T$ is $1-1$.
- If $e_{1}, \ldots, e_{p}$ are linearly independent in $V$, then $T\left(e_{1}\right), \ldots, T\left(e_{p}\right)$ are so in $W$.
- $\operatorname{dim}(W)=n$.


## In finite dimensions

- Let $V$ be f.d with $\operatorname{dim}(V)=n$ and $T: V \rightarrow W$ is an onto linear map. Then TFAE (HW):
- $T$ is $1-1$.
- If $e_{1}, \ldots, e_{p}$ are linearly independent in $V$, then $T\left(e_{1}\right), \ldots, T\left(e_{p}\right)$ are so in $W$.
- $\operatorname{dim}(W)=n$.
- If $e_{1}, \ldots, e_{n}$ is a basis for $V$,


## In finite dimensions

- Let $V$ be f.d with $\operatorname{dim}(V)=n$ and $T: V \rightarrow W$ is an onto linear map. Then TFAE (HW):
- $T$ is $1-1$.
- If $e_{1}, \ldots, e_{p}$ are linearly independent in $V$, then $T\left(e_{1}\right), \ldots, T\left(e_{p}\right)$ are so in $W$.
- $\operatorname{dim}(W)=n$.
- If $e_{1}, \ldots, e_{n}$ is a basis for $V$, then $T\left(e_{1}\right), \ldots, T\left(e_{n}\right)$ is so for W.


## Linear equations

## Linear equations

- Recall that linear systems of equations


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right]$,


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$,


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally,


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e.,


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations.


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the coefficient matrix.


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the coefficient matrix. As mentioned earlier,


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the coefficient matrix. As mentioned earlier, systems can fail to have solutions or even


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the coefficient matrix. As mentioned earlier, systems can fail to have solutions or even have infinitely many solutions.


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the coefficient matrix. As mentioned earlier, systems can fail to have solutions or even have infinitely many solutions.
- If $b=0$, then


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the coefficient matrix. As mentioned earlier, systems can fail to have solutions or even have infinitely many solutions.
- If $b=0$, then the system $A X=0$ is called a homogeneous system.


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the coefficient matrix. As mentioned earlier, systems can fail to have solutions or even have infinitely many solutions.
- If $b=0$, then the system $A X=0$ is called a homogeneous system.
- Recall that


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{c}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the coefficient matrix. As mentioned earlier, systems can fail to have solutions or even have infinitely many solutions.
- If $b=0$, then the system $A X=0$ is called a homogeneous system.
- Recall that if $A X_{0}=b$,


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the coefficient matrix. As mentioned earlier, systems can fail to have solutions or even have infinitely many solutions.
- If $b=0$, then the system $A X=0$ is called a homogeneous system.
- Recall that if $A X_{0}=b$, then any other solution to $A X=b$ is


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the coefficient matrix. As mentioned earlier, systems can fail to have solutions or even have infinitely many solutions.
- If $b=0$, then the system $A X=0$ is called a homogeneous system.
- Recall that if $A X_{0}=b$, then any other solution to $A X=b$ is of the form $X=X_{0}+N$


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the coefficient matrix. As mentioned earlier, systems can fail to have solutions or even have infinitely many solutions.
- If $b=0$, then the system $A X=0$ is called a homogeneous system.
- Recall that if $A X_{0}=b$, then any other solution to $A X=b$ is of the form $X=X_{0}+N$ where $A N=0$.


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the coefficient matrix. As mentioned earlier, systems can fail to have solutions or even have infinitely many solutions.
- If $b=0$, then the system $A X=0$ is called a homogeneous system.
- Recall that if $A X_{0}=b$, then any other solution to $A X=b$ is of the form $X=X_{0}+N$ where $A N=0$. So it suffices to solve $A N=0$ and


## Linear equations

- Recall that linear systems of equations like $2 x+3 y+z=20, x+y-z=\pi$ can be written using matrices as $A X=b$ where $A=\left[\begin{array}{ccc}2 & 3 & 1 \\ 1 & 1 & -1\end{array}\right], X=\left[\begin{array}{l}x \\ y \\ z\end{array}\right]$, and $b=\left[\begin{array}{c}20 \\ \pi\end{array}\right]$.
- More generally, $\sum_{j} A_{i j} x_{j}=b_{i}$, i.e., $A X=b$ represents a system of linear equations. The matrix $A$ is called the coefficient matrix. As mentioned earlier, systems can fail to have solutions or even have infinitely many solutions.
- If $b=0$, then the system $A X=0$ is called a homogeneous system.
- Recall that if $A X_{0}=b$, then any other solution to $A X=b$ is of the form $X=X_{0}+N$ where $A N=0$. So it suffices to solve $A N=0$ and find a single solution to $A X=b$.


## Solving linear equations

## Solving linear equations

- So how does one solve linear equations?


## Solving linear equations

- So how does one solve linear equations?
- One is allowed to


## Solving linear equations

- So how does one solve linear equations?
- One is allowed to
- Interchange equations.


## Solving linear equations

- So how does one solve linear equations?
- One is allowed to
- Interchange equations.
- Multiply both sides of


## Solving linear equations

- So how does one solve linear equations?
- One is allowed to
- Interchange equations.
- Multiply both sides of an equation by a


## Solving linear equations

- So how does one solve linear equations?
- One is allowed to
- Interchange equations.
- Multiply both sides of an equation by a nonzero scalar.


## Solving linear equations

- So how does one solve linear equations?
- One is allowed to
- Interchange equations.
- Multiply both sides of an equation by a nonzero scalar.
- Add one equation to a multiple of another.


## Solving linear equations

- So how does one solve linear equations?
- One is allowed to
- Interchange equations.
- Multiply both sides of an equation by a nonzero scalar.
- Add one equation to a multiple of another.
- The high-school idea


## Solving linear equations

- So how does one solve linear equations?
- One is allowed to
- Interchange equations.
- Multiply both sides of an equation by a nonzero scalar.
- Add one equation to a multiple of another.
- The high-school idea is to eliminate a few variables and


## Solving linear equations

- So how does one solve linear equations?
- One is allowed to
- Interchange equations.
- Multiply both sides of an equation by a nonzero scalar.
- Add one equation to a multiple of another.
- The high-school idea is to eliminate a few variables and solve for the rest by "back-substitution".


## Solving linear equations

- So how does one solve linear equations?
- One is allowed to
- Interchange equations.
- Multiply both sides of an equation by a nonzero scalar.
- Add one equation to a multiple of another.
- The high-school idea is to eliminate a few variables and solve for the rest by "back-substitution".
- This idea was formalised


## Solving linear equations

- So how does one solve linear equations?
- One is allowed to
- Interchange equations.
- Multiply both sides of an equation by a nonzero scalar.
- Add one equation to a multiple of another.
- The high-school idea is to eliminate a few variables and solve for the rest by "back-substitution".
- This idea was formalised and used to great effect


## Solving linear equations

- So how does one solve linear equations?
- One is allowed to
- Interchange equations.
- Multiply both sides of an equation by a nonzero scalar.
- Add one equation to a multiple of another.
- The high-school idea is to eliminate a few variables and solve for the rest by "back-substitution".
- This idea was formalised and used to great effect by Gauss and Jordan.


## Gauss-Jordan elimination

## Gauss-Jordan elimination

- Firstly,


## Gauss-Jordan elimination

- Firstly, in the example above


## Gauss-Jordan elimination

- Firstly, in the example above the variables $x, y, z$ are distractions.


## Gauss-Jordan elimination

- Firstly, in the example above the variables $x, y, z$ are distractions. After all, we only care about manipulating the


## Gauss-Jordan elimination

- Firstly, in the example above the variables $x, y, z$ are distractions. After all, we only care about manipulating the coefficients.


## Gauss-Jordan elimination

- Firstly, in the example above the variables $x, y, z$ are distractions. After all, we only care about manipulating the coefficients.
- So we define the augmented matrix $[A \mid b]$ by simply


## Gauss-Jordan elimination

- Firstly, in the example above the variables $x, y, z$ are distractions. After all, we only care about manipulating the coefficients.
- So we define the augmented matrix $[A \mid b]$ by simply adding $b$ as a column to $A$.


## Gauss-Jordan elimination

- Firstly, in the example above the variables $x, y, z$ are distractions. After all, we only care about manipulating the coefficients.
- So we define the augmented matrix $[A \mid b]$ by simply adding $b$ as a column to $A$.
- Notice that the three "legal" operations


## Gauss-Jordan elimination

- Firstly, in the example above the variables $x, y, z$ are distractions. After all, we only care about manipulating the coefficients.
- So we define the augmented matrix $[A \mid b]$ by simply adding $b$ as a column to $A$.
- Notice that the three "legal" operations alluded to above are:


## Gauss-Jordan elimination

- Firstly, in the example above the variables $x, y, z$ are distractions. After all, we only care about manipulating the coefficients.
- So we define the augmented matrix $[A \mid b]$ by simply adding $b$ as a column to $A$.
- Notice that the three "legal" operations alluded to above are:
- Interchanging the rows of $[A \mid b]$. (


## Gauss-Jordan elimination

- Firstly, in the example above the variables $x, y, z$ are distractions. After all, we only care about manipulating the coefficients.
- So we define the augmented matrix $[A \mid b]$ by simply adding $b$ as a column to $A$.
- Notice that the three "legal" operations alluded to above are:
- Interchanging the rows of $[A \mid b]$. (Each row corresponds to an equation.)


## Gauss-Jordan elimination

- Firstly, in the example above the variables $x, y, z$ are distractions. After all, we only care about manipulating the coefficients.
- So we define the augmented matrix $[A \mid b]$ by simply adding $b$ as a column to $A$.
- Notice that the three "legal" operations alluded to above are:
- Interchanging the rows of $[A \mid b]$. (Each row corresponds to an equation.)
- Multiply any row by a nonzero scalar.


## Gauss-Jordan elimination

- Firstly, in the example above the variables $x, y, z$ are distractions. After all, we only care about manipulating the coefficients.
- So we define the augmented matrix $[A \mid b]$ by simply adding $b$ as a column to $A$.
- Notice that the three "legal" operations alluded to above are:
- Interchanging the rows of $[A \mid b]$. (Each row corresponds to an equation.)
- Multiply any row by a nonzero scalar.
- Add a row to a multiple of another.


## Gauss-Jordan elimination

- Firstly, in the example above the variables $x, y, z$ are distractions. After all, we only care about manipulating the coefficients.
- So we define the augmented matrix $[A \mid b]$ by simply adding $b$ as a column to $A$.
- Notice that the three "legal" operations alluded to above are:
- Interchanging the rows of $[A \mid b]$. (Each row corresponds to an equation.)
- Multiply any row by a nonzero scalar.
- Add a row to a multiple of another.
- These operations are called


## Gauss-Jordan elimination

- Firstly, in the example above the variables $x, y, z$ are distractions. After all, we only care about manipulating the coefficients.
- So we define the augmented matrix $[A \mid b]$ by simply adding $b$ as a column to $A$.
- Notice that the three "legal" operations alluded to above are:
- Interchanging the rows of $[A \mid b]$. (Each row corresponds to an equation.)
- Multiply any row by a nonzero scalar.
- Add a row to a multiple of another.
- These operations are called elementary row operations.


## Row-echelon form

## Row-echelon form

- The aim is to do these operations and


## Row-echelon form

- The aim is to do these operations and bring the matrix to a


## Row-echelon form

- The aim is to do these operations and bring the matrix to a special form (


## Row-echelon form

- The aim is to do these operations and bring the matrix to a special form (known as the row-echelon form).
- The aim is to do these operations and bring the matrix to a special form (known as the row-echelon form).
- A matrix $C$ is said to be
- The aim is to do these operations and bring the matrix to a special form (known as the row-echelon form).
- A matrix $C$ is said to be in the row-echelon form if
- The aim is to do these operations and bring the matrix to a special form (known as the row-echelon form).
- A matrix $C$ is said to be in the row-echelon form if below the first non-zero entry of every row
- The aim is to do these operations and bring the matrix to a special form (known as the row-echelon form).
- A matrix $C$ is said to be in the row-echelon form if below the first non-zero entry of every row all the elements are zero.
- The aim is to do these operations and bring the matrix to a special form (known as the row-echelon form).
- A matrix $C$ is said to be in the row-echelon form if below the first non-zero entry of every row all the elements are zero.
- The point is to
- The aim is to do these operations and bring the matrix to a special form (known as the row-echelon form).
- A matrix $C$ is said to be in the row-echelon form if below the first non-zero entry of every row all the elements are zero.
- The point is to solve the last non-trivial equation and
- The aim is to do these operations and bring the matrix to a special form (known as the row-echelon form).
- A matrix $C$ is said to be in the row-echelon form if below the first non-zero entry of every row all the elements are zero.
- The point is to solve the last non-trivial equation and back-substitute to solve the rest.


## Examples and non-examples of row-echelon matrices

## Examples and non-examples of row-echelon matrices

$-\left[\begin{array}{lll}2 & 3 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0\end{array}\right]$ is

## Examples and non-examples of row-echelon matrices

- $\left[\begin{array}{lll}2 & 3 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0\end{array}\right]$ is not in the row-echelon form.


## Examples and non-examples of row-echelon matrices

- $\left[\begin{array}{lll}2 & 3 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0\end{array}\right]$ is not in the row-echelon form.
$-\left[\begin{array}{ll}\pi & 2 \\ 0 & e\end{array}\right]$ is
- $\left[\begin{array}{lll}2 & 3 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0\end{array}\right]$ is not in the row-echelon form.
- $\left[\begin{array}{ll}\pi & 2 \\ 0 & e\end{array}\right]$ is in the row-echelon form.
- $\left[\begin{array}{lll}2 & 3 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0\end{array}\right]$ is not in the row-echelon form.
- $\left[\begin{array}{ll}\pi & 2 \\ 0 & e\end{array}\right]$ is in the row-echelon form.
- $\left[\begin{array}{cc}\sqrt{-1} & 1 \\ 0 & 1 \\ 0 & 0\end{array}\right]$ is
- $\left[\begin{array}{lll}2 & 3 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0\end{array}\right]$ is not in the row-echelon form.
- $\left[\begin{array}{ll}\pi & 2 \\ 0 & e\end{array}\right]$ is in the row-echelon form.
- $\left[\begin{array}{cc}\sqrt{-1} & 1 \\ 0 & 1 \\ 0 & 0\end{array}\right]$ is in the row-echelon form.

