Higher Engineering Mathematics
Prof. P. N. Agrawal
Department of Mathematics
Indian Institute of Technology, Roorkee
Lecture 33 – Representation of Graphs

Hello friends! Welcome to my lecture on Representation of Graphs. Although a diagrammatic representation of a graph is very convenient for visual study but this is only possible when the number of nodes and edges is reasonably small. Now there are two types of representations. Matrix representation, let us consider the matrix representation. The matrices are commonly used to represent graphs for computer processing.

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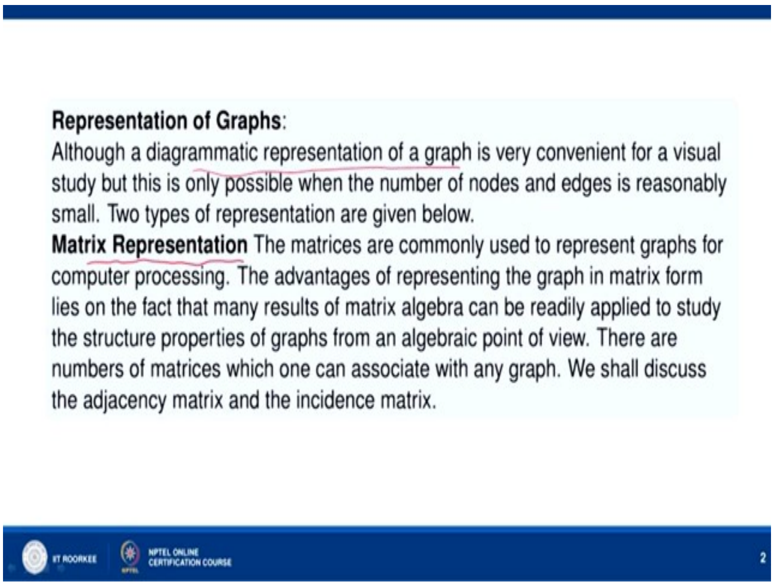

The advantages of representing the graph in matrix form lies in the fact that many results of matrix algebra can be readily applied to study the structure properties of graphs from an algebraic point of view. There are number of matrices which one can associate with any graph. Let us discuss the adjacency matrix and the incidence matrix.

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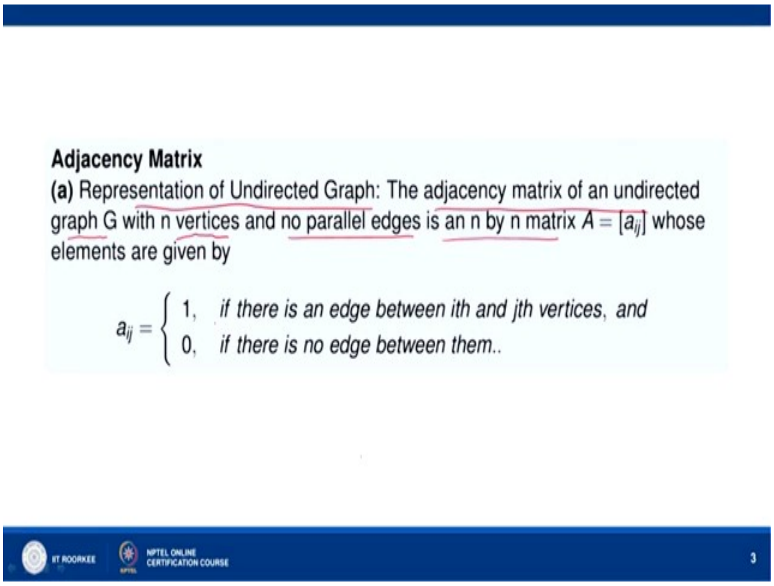

Let us first discuss adjacency matrix. Representation of an undirected graph, suppose we want to represent an undirected graph, then the adjacency matrix of an undirected graph G with n vertices and no parallel edges is an $n \times n$ matrix A= a_{ij}, where elements are given by a_{ij} equal to 1 if there is an edge between ith and jth vertices, and 0 if there is no edge between them.

So when we consider the case of an undirected graph where there are n vertices and no parallel edges, we will have $n \times n$ matrix. And the (i,j)th entry of that $n \times n$ matrix is defined as equal to 1 if there is an edge between ith and jth vertices, and 0 if there is no edge between them.

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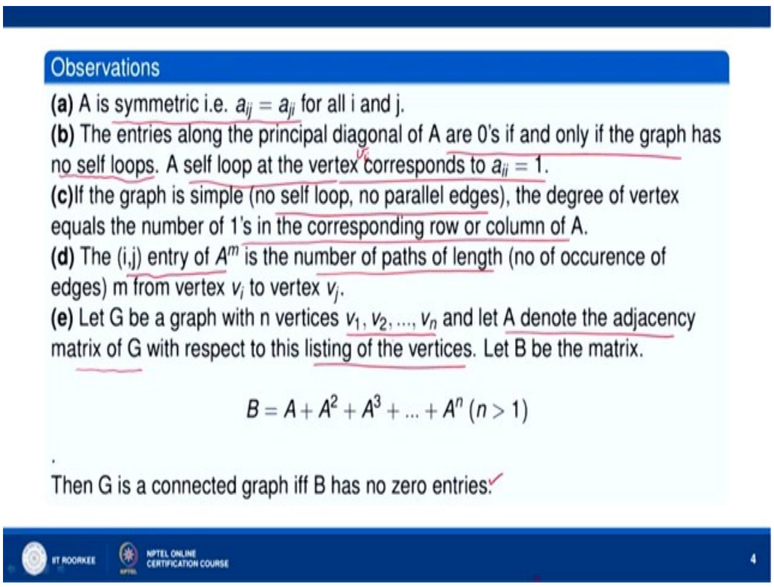

Now let us look at certain some observations of these adjacency matrices. We shall see that A is a symmetric matrix, a_{ij} equal to a_{ji} for all i and j. Because if there is an edge between ith and jth vertices, then a_{ij} will have value 1 and also a_{ji} will have value 1 because it is an undirected graph. Now the entries along the principal diagonal of A are zeroes if and only if the graph has no self loops.

So when the graph has no….Because the diagonal entries are given by a_{11},a_{22} , and so on, a_{nn}, so that means if there are no self loops, then a_{11}, a_{22}, a_{33} and so on, a_{nn} will all be zeroes. So the entries along the principal diagonal of A are zeroes if and only if the graph has no self loops.

Now a self loop at the vertex corresponds to a_{ii} equal to 1.So if there is a self loop at the vertex it corresponds to the entry of the main principal diagonal a_{ii}equal to 1. The vertex, say, but the vertex is V_i, at the vertex $V_i$there is a self loop, then the corresponding….because a_{ii} means the edge from $V_i$to V_i, so if there is a self loop, then a_{ii} will be equal to 1.

Now if the graph is simple, there is no self loop, no parallel edges; then degree of vertex equals the number of 1's in the corresponding row or column of A. Because if there is no self loop or no parallel edges, then how we define the degree of a vertex? Degree of a vertex is the number of edges that are associated with that vertex, that are incident on that. So number of 1's in the corresponding row or columns, because the matrix is symmetric, so we can count the number of 1's occurring in that particular row or column. It will give you the degree of that vertex.

Suppose that vertex V_i, it is associated with V_1, it is associated with V_2, it is associated with V_5, then V_{i1}, V_{i2}, V_{i5}, each will carry value 1. So number of 1's in the ith row or the corresponding column will tell you the degree of the vertex of that. Now i jth entry of A to the power m is the number of paths of length m from vertex V_i to vertex V_j. So i jth entry of A to the power m is the number of paths of length m from vertex $V_i$to vertex V_j. A to the power m means A into A into A, m times.

Now G be a graph with n vertices, let us say G be a graph with n vertices, V_1, V_2,…, $V_n$and let A denote the adjacency matrix of G with respect to this listing of vertices, V_1, V_2,…, V_n.

And let B be the matrix. $B = A + A^2 + A^3 \ldots . + A^n$. Then G is a connected graph if and only if B has no zero entries. Now this can be used to check whether a given graph is connected or not.

So the adjacency matrix can be used to check whether the given graph G is connected or not. So that is one very important use of the adjacency matrices. Now here we are taking one particular order of $V_1, V_2, \ldots, V_n$. There can be n factorial order in which this $V_1, V_2 can, \ldots, V_n$ can be arranged. So there is not one adjacency matrix, there are n factorial adjacency matrices corresponding to the n factorial arrangements of $V_1, V_2, \ldots, V_n$.

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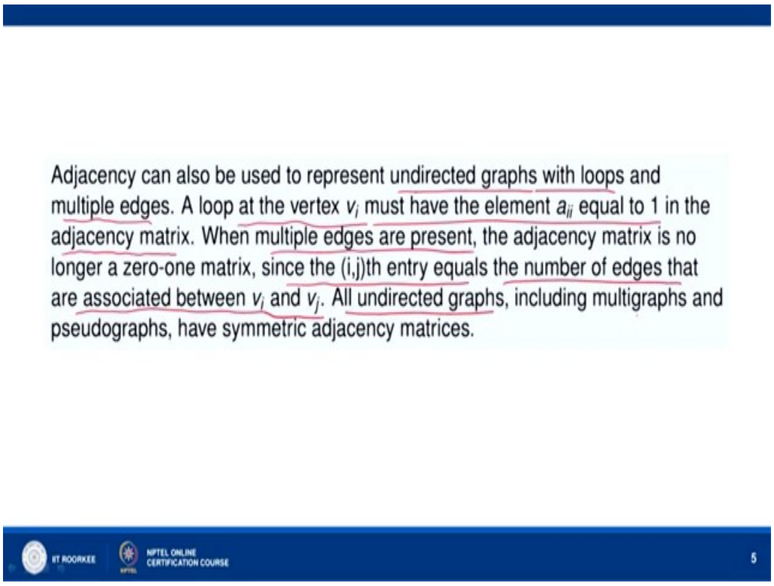

Now let us go to other uses of adjacency matrices. Adjacency matrices can be used to represent undirected graphs with loops and multiple edges. Here we assumed that there were no loops or multiple edges but adjacency matrices can be used to represent undirected graphs with loops and multiple edges also. A loop at the vertex V_1, must have the element a_{ii} equal to 1 in the adjacency matrix. When multiple edges are present, the adjacency matrix is no longer a zero-one matrix, because if at the vertex V_i you see that there are multiple edges, then the entry a_{ii} will not be 1 or 0.

So since the i jth entry equals the number of edges that are associated between V_i and V_j, so if there are multiple edges present, then adjacency matrix will no longer be a zero-one matrix. All undirected graphs, including multigraphs and psuedographs, have symmetric adjacency matrices.

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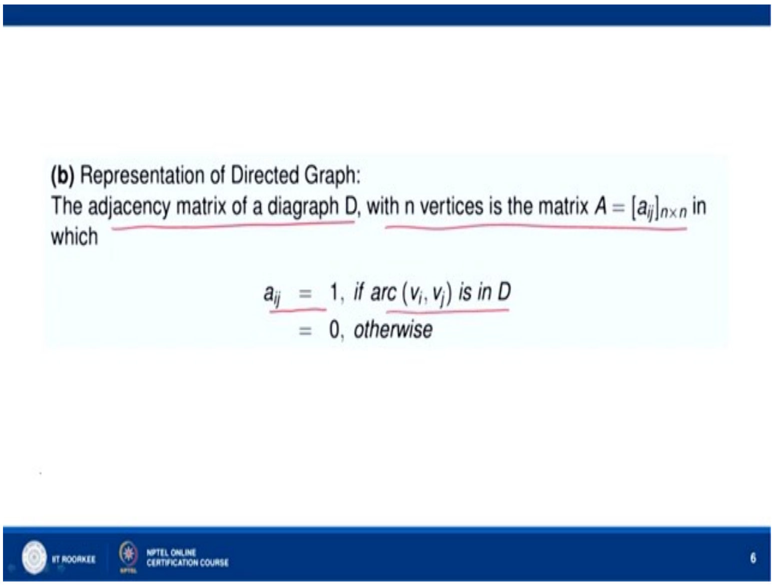

Now representation of a directed graph: The adjacency matrix of a diagraph, directed graph or we can call it diagraph, with n vertices is the matrix A equal to a_{ij}, $n \times n$, in which a_{ij}, is equal to 1 if arc V_i, V_j is in D. So if V_i and V_j are joined by an arc, then a_{ij}, will have value 1, otherwise it will have value 0.

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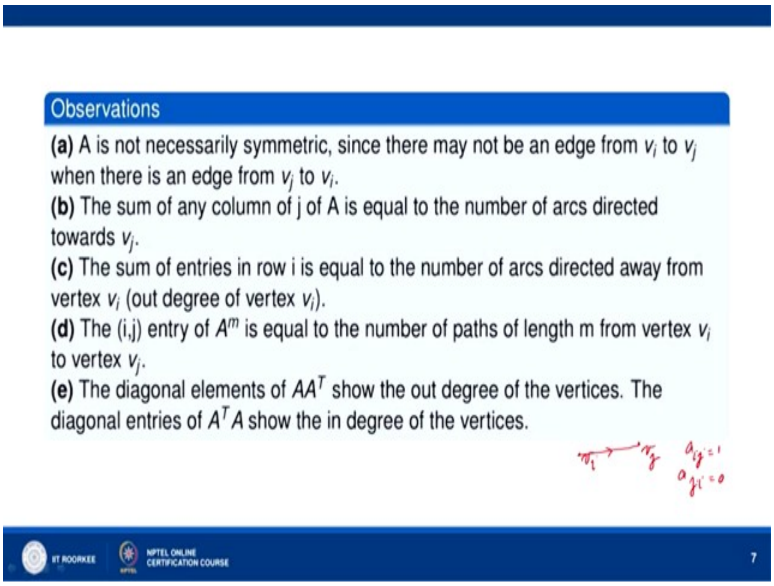

So let us now go to observations regarding the adjacency matrix in the case of diagraph: A is not necessarily symmetric, since there may not be an edge from V_i to V_j. Because it is a directed graph, so suppose this is your vertex V_i and here is the vertex V_j, we may have the direction associated with this edge, it is from V_i to V_j. So then a_{ij} will have value 1 but a_{ji} will have value 0 because the direction is from V_i to V_j , not from V_j to V_i .

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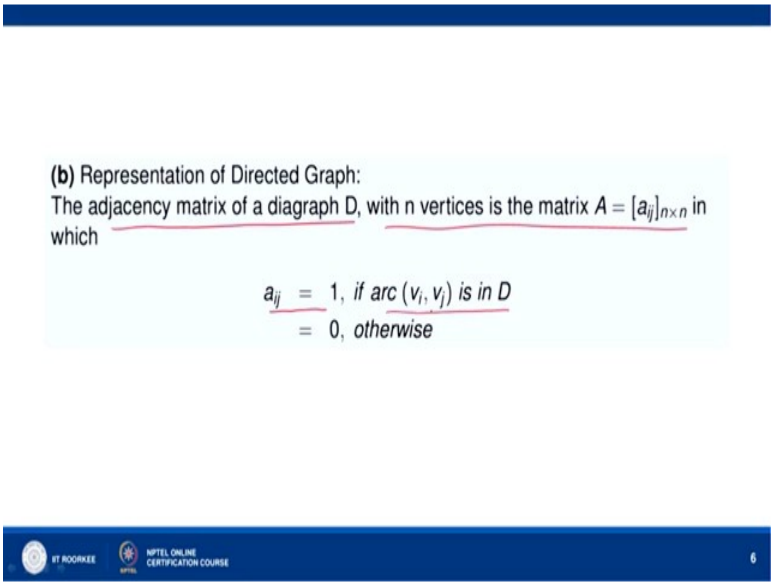

As we have seen here V_i, V_j, V_i, V_j means the direction is from V_i to V_j. V_i is initial point and V_j is terminal point of the edge.

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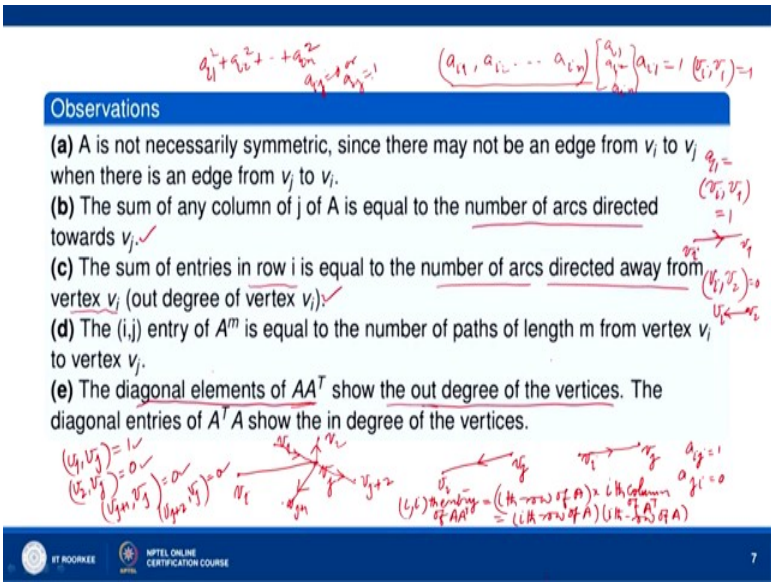

So the A is not necessarily symmetric since there may not be an edge from V_i to V_j when there is an edge from V_j to V_i. So if there is an edge from V_j to V_i, it could be like this also. There is an edge from V_j to V_i but there is no edge from V_i to V_j. Now the sum of any column of, column j of A is equal to the number of arcs directed towards V_j. If you take the jth column of the adjacency matrix A, then sum of the entries of the jth column gives you the number of arcs that are directed towards V_j.

So this is suppose your V_i , this is V_j and then you have other vertices, say, V_j + 1, V_j + 2….you have V_1 , V_2 , so suppose they are joined like this, we can take multiple edges, we can take multiple edges here. So then suppose situation is like this: V_i to V_j like this; then V_j , V_j + 1 will be equal to 1. And V_j , V_j + 1 will be equal to 1. This is V_j + 2. So V_j , V_j +2 will be….we are calling…we are taking column j, so V_{1j} , V_{2j} , that we have to consider. We will write that, not this.

Okay, we are talking about jth column. So jth column means we have to see what is V_1 , V_j ; V_1 , V_j , since the direction is from V_1 ,to V_j , so we have V_1 , V_j equal to 0. V_1 , V_j equal to 0 in the jth column. V_1 , V_j equal to 1, not 0. V_2 , V_j ;V_2 , V_j equal to 0 because it is from , V_j¿V_2, not V_2 to V_j. And then suppose it is….there is this one V_j we can say, say this is V_j plus 1 in the jth column, then V_j +1, V_j is equal to 0 and in this situation we have V_j + 2, V_j equal to 0 because V_j + 2 to V_j we do not have any edge.

So now you can see, suppose this is the situation for, others are all zeroes, the situation is only like this. So then V_1, 0, 0, 0, other entries are all zeroes. Then we will have sum of the entries of the jth column, sum of the entries of the jth column will be 1. So that will tell us the number of arcs directed towards V_j. So this you can see here, V_1 to V_j is equal to 1. So number of sum of the column of, jth column of A tells us the number of arcs that are directed towards V_j.

Because for arcs that are directed towards V_j, for them the value of the a_{ij} will be equal to 1 for all, for i equal to 1, or i equal to 2 or i equal to 3. So the number of, if you consider the sum of the entries in the jth column, it gives us the number of arcs that are directed towards V_j. Now sum of entries in the row i is equal to number of arcs that are directed away from the vertex V i. Because here what happens is in the row i the entries will be like this: a_{i1}, a_{i2},…., $a_{¿}$.

So a_{i1} equal to 1 means what? a_{i1} equal to 1 means V_i, V_1equal to 1. a_{i1} equal to 1 means V_i, V_1 equal to 1. And V_i,V_1 equal to 1 means the direction from V_i to V_1. So they are directed away from V_i. So sum of entries in row i is equal to number of arcs directed away from the vertex V_i. That is out degree of V_i. Here this is in degree of V_j. So the i, j entry of A to the power m is equal to the number of paths of length m from vertex V_i to vertex V_j.

The diagonal elements of $AA^{\prime}$ show the out degree of the vertices. When you consider $AA^{\prime}$, $AA^{\prime}$ means you multiply the elements of ith row of A by the jth column of $A^{\prime}$, if you have AB, we multiply ith row of A by jth column of B. So a_{ij}, becomes, ith row of A will become there ith column of B, so we will have out degree of the vertices. I multiply ith row of A, okay let us see, we have ith row, a_{i1}, a_{i2},….If you find the i jth element of $AA^{\prime}$, i jth entry of $AA^{\prime}$ equal to ith row of A multiplied by, ith row of A into, multiplied by jth column of A transpose.

So ith row of A will give you diagonal elements of A A transpose. Diagonal elements of $AA^{\prime}$ means ith row….okay, diagonal elements of $AA^{\prime}$ means i ith entry. i ith entry of $A^{\prime}$ means ith row of A into ith column of….okay i ith…because we are talking about diagonal elements of $AA^{\prime}$. So this means ith row of A into ith column of $A^{\prime}$. ith column of $A^{\prime}$ means ith row of A into ith row of A.

i ith entry of $AA^{\prime}$ means ith row of A, product of that with ith column of $A^{\prime}$. ith column of $A^{\prime}$ is ith row of A. So ith row of A if it is a_{i1}, a_{i2},…, $a_{¿}$, then the diagonal element i i will be becoming $a_{i1}^2+a_{i2}^2$ +…., $a_{¿}^2$. And the sum of entries in row i is equal to sum of arcs directed away from the vertex V i. So diagonal elements show the out degree of the vertices.

i jth entry will be equal to $a_{i1}^2+a_{i2}^2$ +…., $a_{¿}^2$. Now either the value of these are 1's or they are zeroes. So see, we have diagonal elements of $AA^{\prime}$, the out degree of the vertices because i ith entry of, that is i ith entry of $AA^{\prime}$ is ith row of A into ith column of $A^{\prime}$ which is ith row of A into ith row of A. So ith row of A is a_{i1}, a_{i2},,…, $a_{¿}$.

And when you multiply a_{i1}, a_{i2},,…, $a_{¿}$and this row by the column a_{i1}, a_{i2},,…, $a_{¿}$ what we get is $a_{i1}^2+a_{i2}^2$ +…., $a_{¿}^2$. And a_{i1}, a_{i1} means what? a_{i1} means V_i,V_1.V_i,V_1. will have value 1. If V_i. vertex, it will have value 1 if that the edge is directed from V_i. towards V_1. And V_i, V_j. similarly will be equal to 0 if V_i. is directed, when V_j. is directed towards V_i. So then it will be 0.

So what will happen if it is 1, it is 0, and so on, it is 1? So the sum of these 1's they will tell us the out degree of V_i. Because either the value of a_{ij} equal to 0, a_{ij} equal to 0 or a_{ij} equal to 1. So diagonal elements tell us the out degree of the vertices. Similarly, diagonal entries of $A^{\prime}$A tell us the in degree of the vertices.

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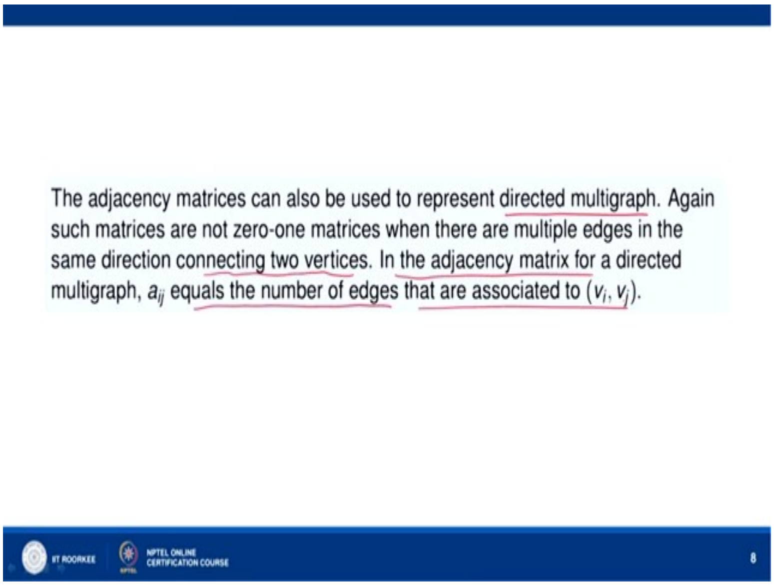

Now the adjacency matrices can also be used to represent directed multigraph. Such matrices are not zero-one matrices when there are multiple edges in the same direction connecting the two vertices. So such matrices cannot be zero-one matrices. In the adjacency matrix for a directed multigraph, a_{ij} equals the number of edges that are associated with V_i, V_j. So if there are multiple edges, a_{ij} then will equal to the number of edges that are associated to V_i, V_j.

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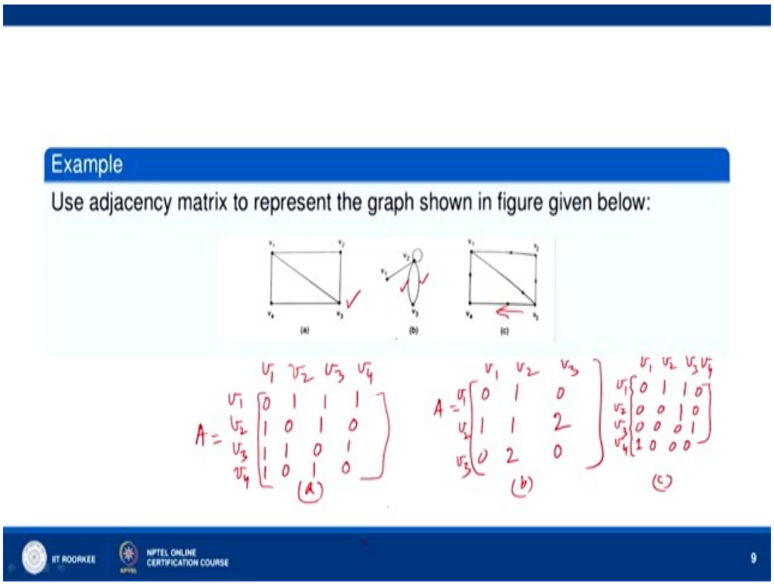

Now let us see, let us use adjacency matrix to represent the graph shown in this figure. So here we can see we have four vertices: V_1, V_2, V_3, V_4. So we will have $n \times n$matrix that is 4×4 matrix here. Now there is no self loop at V_1, so V_1, V_1 is, so a_{11} is equal to 0. a_{12}, okay, now V_1 is connected to V_2, there is edge between V_1 and V_2, so V_1, V_2, a_{12} is equal to 1.

Then V_1, V_3, okay, V_1, V_3 are joined, so a_{13}, is equal to 1. Then V_1, V_4, that is also, there is an edge between V_1 and V_4, so this is equal to 1. V_2, V_1; V_2, V_1 is also equal to 1. And moreover, this matrix is symmetric, so first row will be same as first column. So we can write like this. And then V_2, V_2 there is no self loop at V, so we have V_2, V_2, 0. So V_2, V_3; V_2 is joined to V_3, so we have 1. V_2, V_4; there is no edge between V_2 and V_4, so we get 0.

And then V_3, so 1, 0, 1, 0; so we have 1, 0, 1, 0. Now consider V_3, V_3; there is no self loop at V_3, so we get 0. V_3, V_4; V_3, V_4 is 1 because V_3 is joined toV_4 by an edge. And then V_4, okay so we have 1, 1, 0, 1. Now V_4, at V_4 there is no self loop, so we get the value 0. So for this adjacency matrix is this. And in this case part 2, let us find the adjacency matrix for part 2.

So here A will be equal to, now we have three vertices; V_1, V_2, V_3; V_1, V_2, V_3. So at V_1 there is no self loop, so we get 0. And then V_1 is joined to V_2, so we have value 1.V_1 is not joined to V_3 by an edge, so we get 0. And then we have symmetric matrix, so 0, 1, 0…okay, so there is a self loop, so let us see. V_2, V_1; V_2 is joined to V_1, so we get 1 here. And then V_2, at V_2 there is a self loop, so we get value 1.

So it is not a symmetric matrix you can see. And then V_2 is joined to V_3, so we get V_2 is joined to….And there are multiple edge between V_2 and V_3, this and this, so V_2, V_3 equal to 2. Now V_3 V_1; V_3, V_1, okay 0. And then V_3, V_2; V_3,V_2 equal to 2. And then V_3, V_3 is 0. So this is the adjacency matrix for this problem here. It is not symmetric because in this graph there are multiple edges and self loop. There is one self loop and we have two multiple edges.

Now in the part (c), so this is part (b), in the part (c) we have four vertices: so V_1, V_2, V_3, V_4; and V_1, V_2, V_3, V_4. Now let us see what is the matrix. So V_1, at V_1 there is no self loop, so we get 0. V_1 is joined to V_2, so we get value 1. V_1 is joined to V_3, so we get value 1. V_1 is joined to V_4, we get value 1. And then V_2, V_1; $V_2$is joined to…Oh! Sorry, it is a directed graph, so we have to see that.

So V_1 to V_1; $V_1$to $V_1$is 0. Now V_1 to V_2; $V_1$to $V_2$is 1. Then V_1 to V_3; V_1 to V_3 is 1. $V_1$to V_4 is 0. Because we have V_4 to V_1, not V_1 to V_4, so $V_1$to $V_4$is 0. V_2, V_1; V_2, V_1 is 0. And then V_2 , V_3 ; V_2, $V_3$is also 0. V_2, V_3; V_2, V_2 is 0.V_2 , V_2 is 0 because at V_2 there is no self loop, so we get 0. V_2, V_3; V_2,V_3 is 1. AndV_2 , V_4; V_2, V_4 is 0. And then we get V_3, V_1; V_3, V_1 is 0.

And then we get V_3 , V_2; V_3, V_2 is 0. Then we get V_2 , V_3 ; that is 0. V_3 , V_4 ; V_3 , V_4 is also 0. No, V_3 , V_4 is 1 because we have this direction. And then V_4 , V_1 ; V_4 , V_1 is equal to 1, this is 1. Okay, V_4 , V_1 equal to, is 1. Then V_4 , V_2; V_4 , V_2 is 0. V_4 , V_3 ;V_4 , V_3 is 0. And V_4 , V_4 ; it is 0. So these are the adjacency matrices in the case of undirected graph and directed graph. These two are undirected graphs.

First a part, (b) part are undirected graphs. (c) part is a directed graph. In the part (a), there are no multiple edges and self loops. In the part (b), there are multiple edges and self loops. So in the case of a directed graph, we have to take care of the direction.

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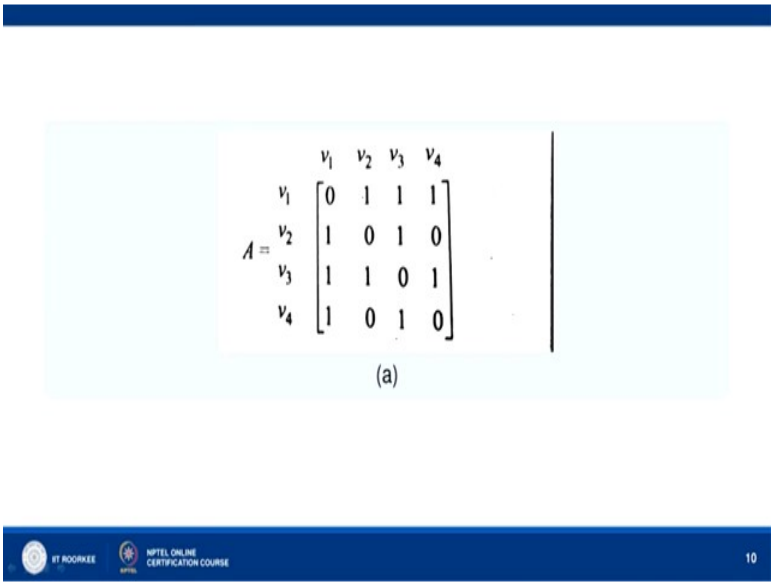

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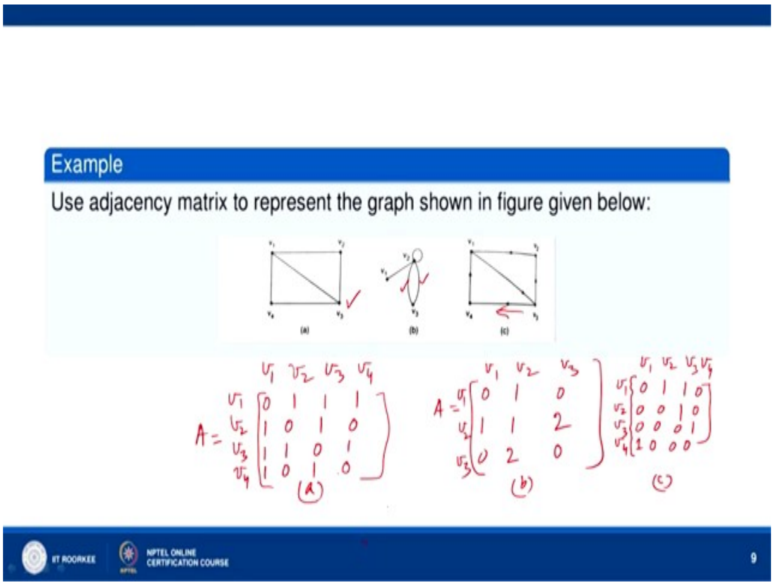

So this is the matrix to the part (a), adjacency matrix to the part (a). We can see 0, 1, 1, 1; 1, 0, 1, 0; 1, 1, 0, 1; 1, 0, 1, 0. So that is adjacency matrix for part (a).

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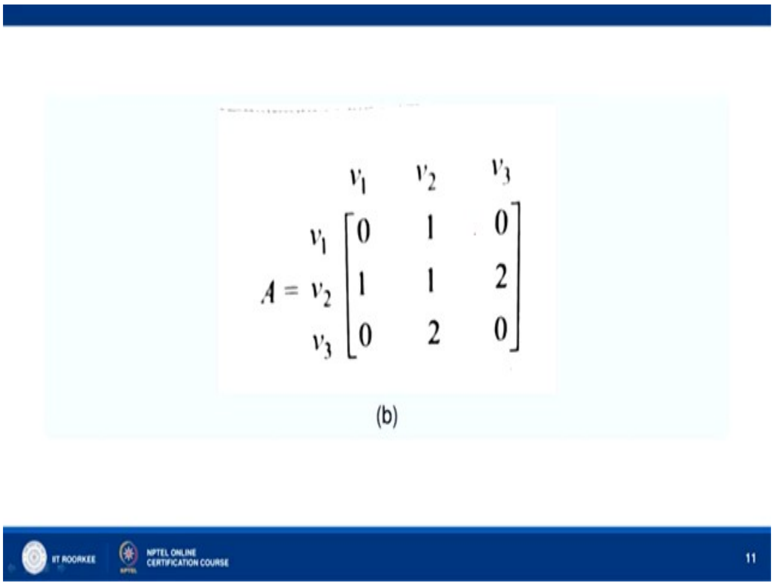

Then adjacency matrix for part b: 0, 1, 0; 1, 1, 2; and then 0, 2, 0.

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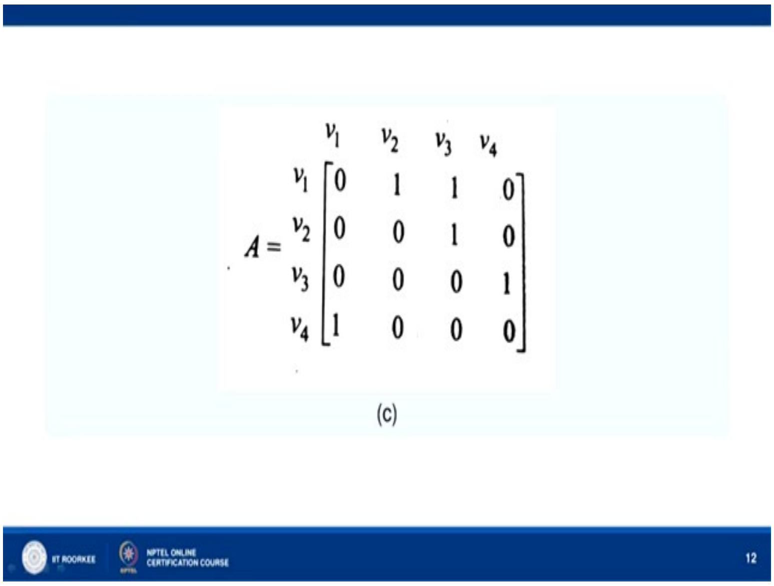

And then we have adjacency matrix for part 3. Let us see that one also. So we have 0, 1, 1, 0; then 0, 0, 1, 0; then 0, 0, 0, 1; then 1, 0, 0, 0.

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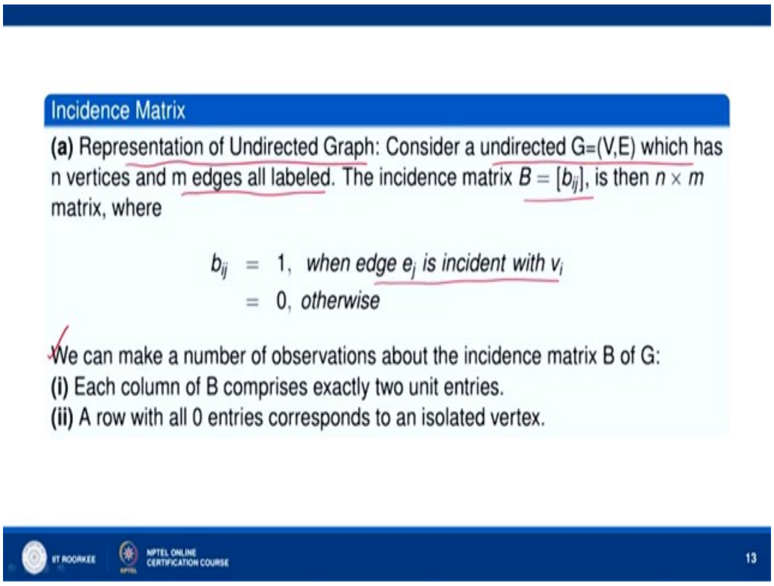

Now let us go to incidence matrix. Representation of an undirected graph, first we discuss this. Consider an undirected graph G =G(V, E) which has n vertices and m edges all labelled. Now the incidence matrix B equal to b_{ij} , is then $n \times m$ matrix, where b_{ij} equal to 1 when edge e_j is incident with V_i, otherwise 0. Let us make a number of observations about the incidence matrix, B of G: A row with all 0 entries corresponds to an isolated vertex. If there is an isolated vertex, then no edge is incident on it. So corresponding to that isolated vertex, row will have all 0 entries.

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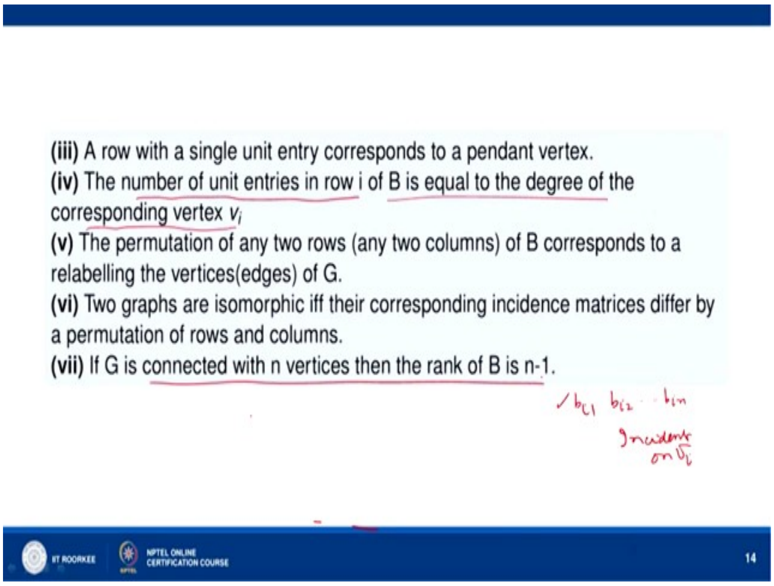

Now a row with a single unit entry correspond to a pendant vertex. The number of unit entries in row i is equal to the degree of the corresponding vertex V_i. Because the row V_i will contain V_{i1}, V_{i2},,…,$V_{¿}$, so this means V_{i1}, V_{i2},,…,$V_{¿}$, the number of unit entries in that will tell you that the how many edges incident on V_i. The number of unit entries in this row, ith row will tell us the number of edges that are incident on V_i. So it will tell us the degree of the vertex V_i.

The permutation of any two rows or any two columns of B corresponds to a relabelling of the vertices of G. Now two graphs are isomorphic if and only if their corresponding incidence matrices differ by a permutation of rows and columns. If G is connected with n vertices then the rank of B = n-1.

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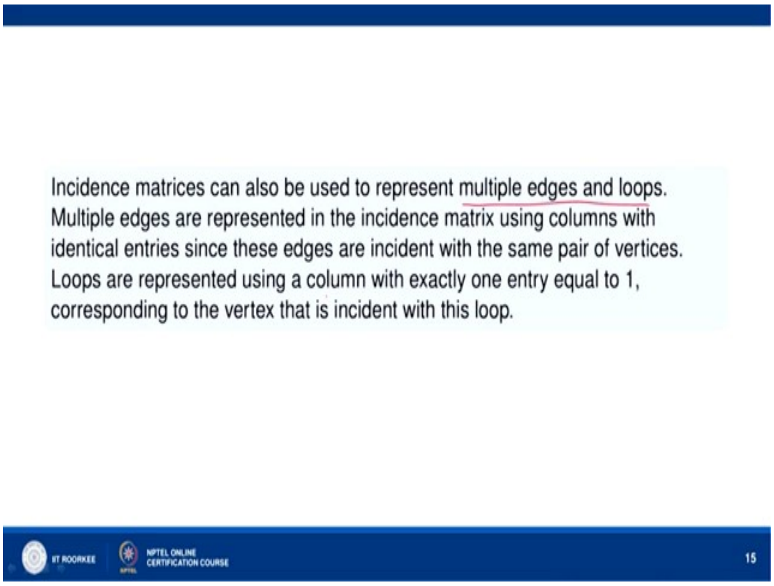

Incidence matrices can also be used to represent multiple edges and loops. Multiple edges are represented in the incidence matrix using columns with identical entries since these edges are identical with the same pair of vertices. Loops are represented using a column with exactly one entry equal to 1, corresponding to the vertex that is incident with this loop.

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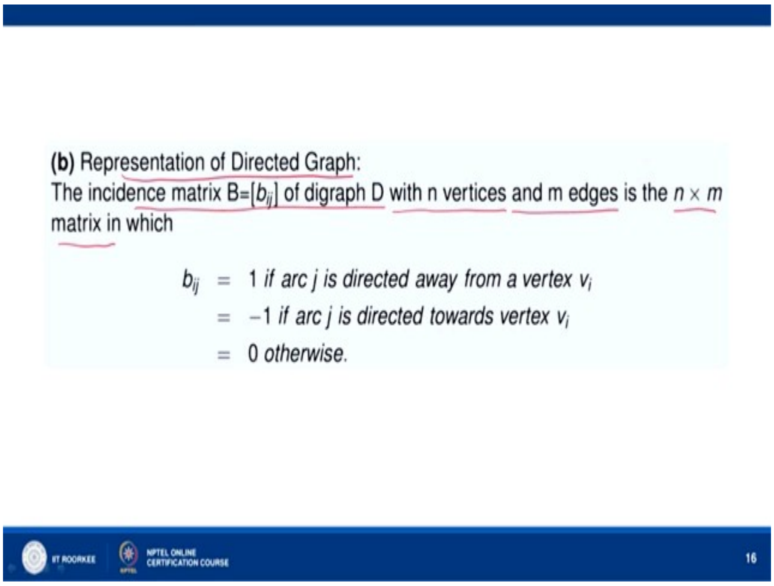

Let us look at some more, this definition, representation of directed graph: The incidence matrix B equal to b_{ij} of diagraph with n vertices and m edges is n×m matrix, in which b_{ij} equal to 1 if arc j is directed away from a vertex V_i. So if arc j is directed away from vertex V_i,b_{ij}will have value 1. If arc j is directed towards vertex V_i, b_{ij}will have value -1, it will have value 0 otherwise.

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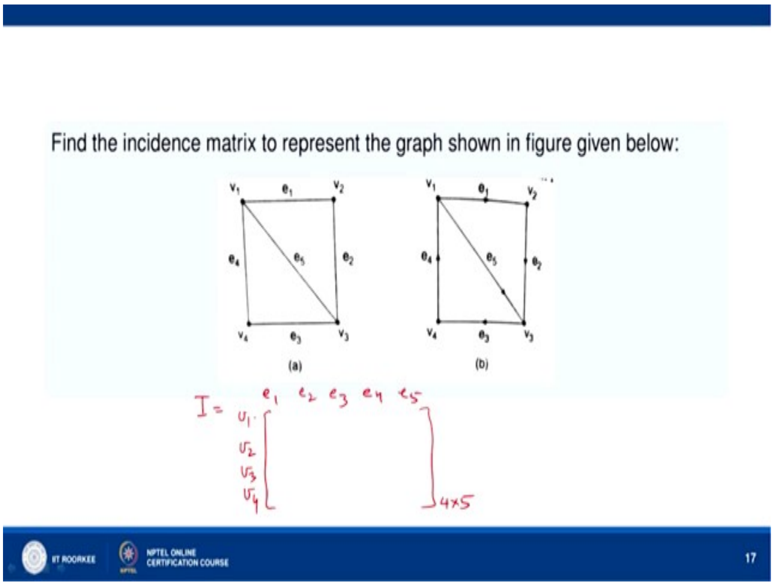

Let us say for example this undirected graph, this undirected graph, so let us see for this graph. We have the matrix, incidence matrix I, so we have, just a minute….Okay, we have the incidence matrix I: We have e_1, e_2, e_3…There are five edges; e_1, e_2, e_3, e_4, e_5. And there are four vertices; V_1,V_2, V_3, V_4. So we will have n×m matrix. n is the number of vertices, so 4 × 5 matrix. n is the number of vertices, 5 is the number of edges.

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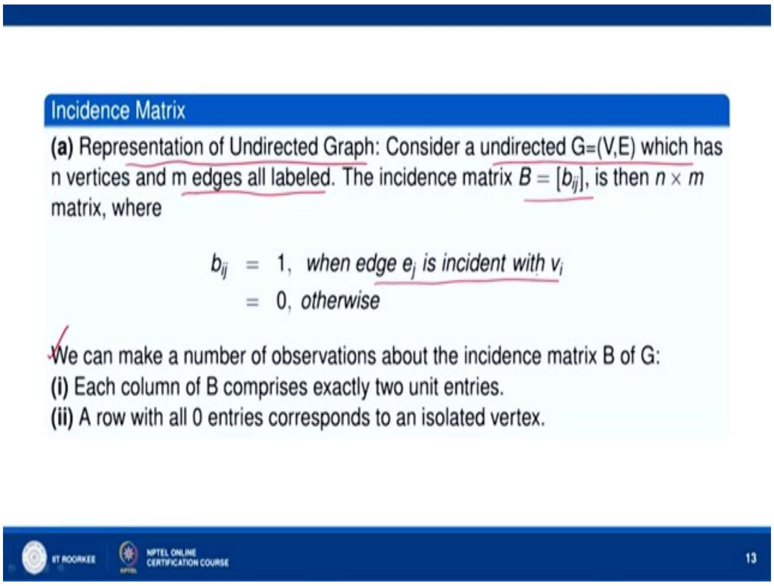

So let us see how we defined…yeah, because we are dealing with undirected graphs, b_{ij}equal to 1 when edge e_j is incident with V_i.

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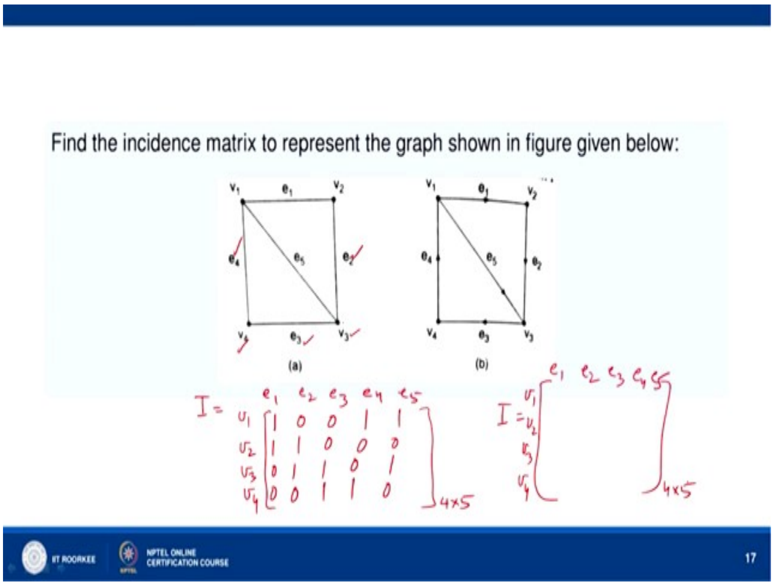

Let us see, e_1 is incident with the vertex V_1, so we will have this V_1 equal to 1. Then e_2 is not incident on V_1, so we have 0. e_3 is not incident on V_1, so we will get value 0. e_4 is incident on V_1, you can see this e_4. It is incident on V_1, so we get value 1. e_5 is incident again on V_1, this e_5, this is incident on V_1, so we will get 1.

V_2,sorry, e_1 is incident on V_2, so we will get value 1. e_2 is incident on V_2, so we will get value 1. e_3 is incident on V_2, no, e_3 is incident on V_2, e_3 is here, it is not incident on V_2, so we will get value 0. And e_4 is not incident on V_2, so it is 0. e_5 is not incident onV_2, so we will get 0. Then e_1, is it incident on V_3? No. e 1 is not incident on V_3. e_2 is incident on V_3, e_2 is incident on V_3, yes. e_2 is here, V_3 is here. So it is incident on V_3, so we will get value 1.

e_3 is incident on V_3? Yes. e_3 is here and V_3 is here, so we get 1 here. Then e_4 is incident on V_3? e_4 incident on V_3, no. Then e_5 incident on V_3? Yeah, e_5 is incident on V_3, so we get 1. Then e_1 is incident on V_4? e_1 is not incident on V_4, so we get 0. e_2 is incident onV_4? No. e_3 is incident on V_4? Yeah, so we have 1 here, e_3 is incident on V_4. And e_4 is incident on V_4? Yes, it is incident on V_4, so we get 1 here. And then e_5, is it incident on V_4? No. So we get 0 here.

So this is incidence matrix for this undirected graph. And in the case of this directed graph, we have I equal to, so we will have, how many vertices are there? 1, 2, 3, 4. So V_1,V_3, V_4. And the edges are e_1, e_2, e_3, e_4 and e_5. So again 4×5 matrix we will have. Now let us see how we define for a directed graph, the incidence matrix.

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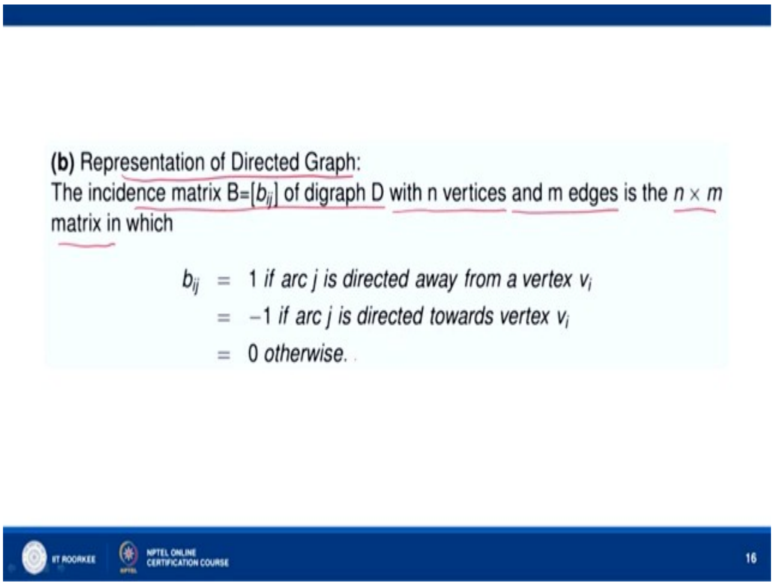

b_{ij} equal to 1 if arc j is directed away from vertex V_i, so let us see. And if it is directed towards we put -1.

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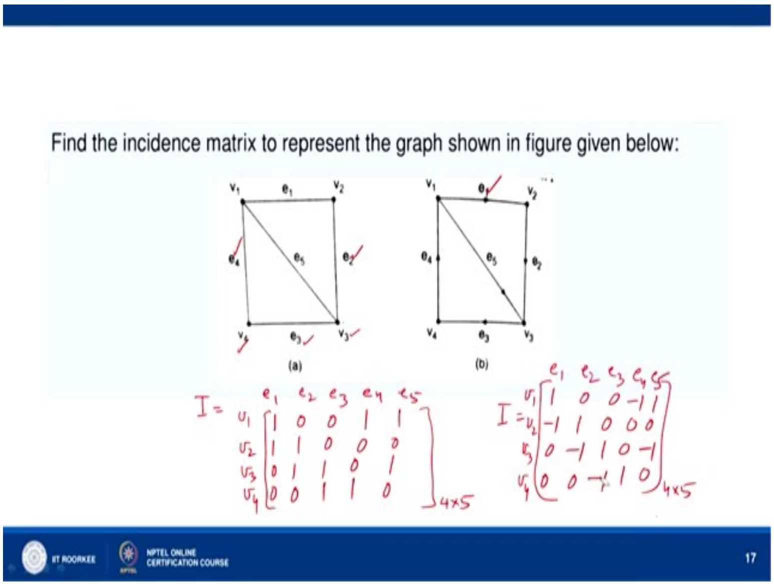

So here e_1, is it directed towards arc? Directed away. e_1 is directed away from V_1 And when it is directed away from V_1, we put 1. So e_1 is directed away from V_1, so we put 1 here. e_2 directed, e_2, V_1, e_2 is here and V_1 is here. So there is no relation between e_2 and V_1. So we put 0 here.

e_3, V_1; e_3 is here, V_1 is there, so this is also 0. e_4 is directed towards V_1, and when it is directed towards V_1, we put -1. So we put -1 here e_5; e_5 is directed away from V_1, so we put 1 here. And then V_2, sorry, e_1 is directed towards V_2, towards V_1 means -1, so we put -1 here. e_2 is directed away from V_2, away from V_2 means plus 1. And then e_3, where is e_3? $e_3$is here and V 2 is there. So we put 0.

e_4,e_4 is here, V_2 is there, so we put 0. e_5, $e_5$is here, V_2 is there, so this is 0. And then e_1, V_3; e_1 is here, V_3 is here, so 0. e_2, V_3; e_2 is directed towards V_3, directed towards V_3 means -1. e_3, e_3 is directed away from V_3, so we put 1 here. e_4 is here, V_3 is there, so we put 0. e_5, V_3; e_5 is directed towards V_3, towards V_3 means -1. And then V_4; e_1 is directed....V_4 is here, so this is 0. e_2 is again here and V_4 is there. e_3 is directed towards V_4, so we get minus 1. e_4 is directed away from V_4, so we get plus 1. And then e_5, e_5 is here, V_4 is there, so we put 0 here. So this is how we write the incidence matrix for this directed graph.

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$$I(G) = \begin{array}{c c} & \begin{array}{ccccc} e_1 & e_2 & e_3 & e_4 & e_5 \end{array} \\ \begin{array}{c} v_1 \\ v_2 \\ v_3 \\ v_4 \end{array} & \begin{bmatrix} 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 \end{bmatrix} \end{array}$$

(a)

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So this is the incidence matrix for the undirected graph. 1, 0, 0, 1, 1; 1, 1, 0, 0, 0; we get 0, 1, 1, 0, 1 and then 0, 0, 1, 1, 0.

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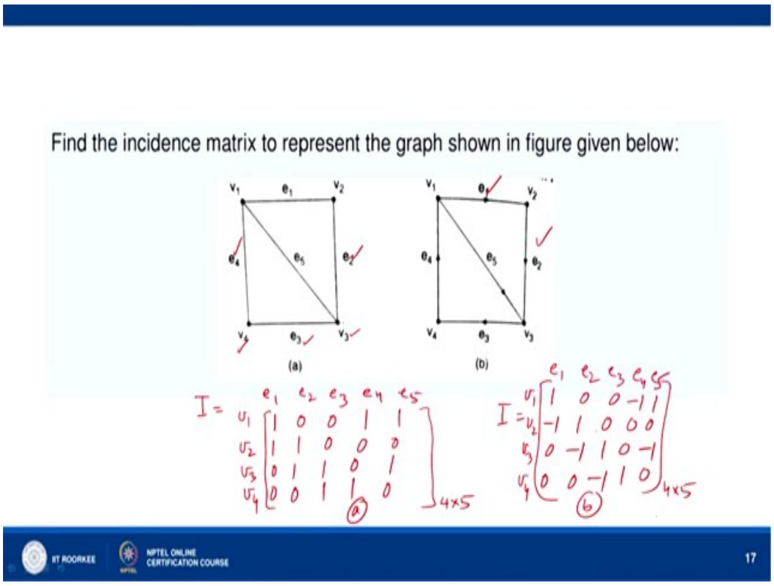

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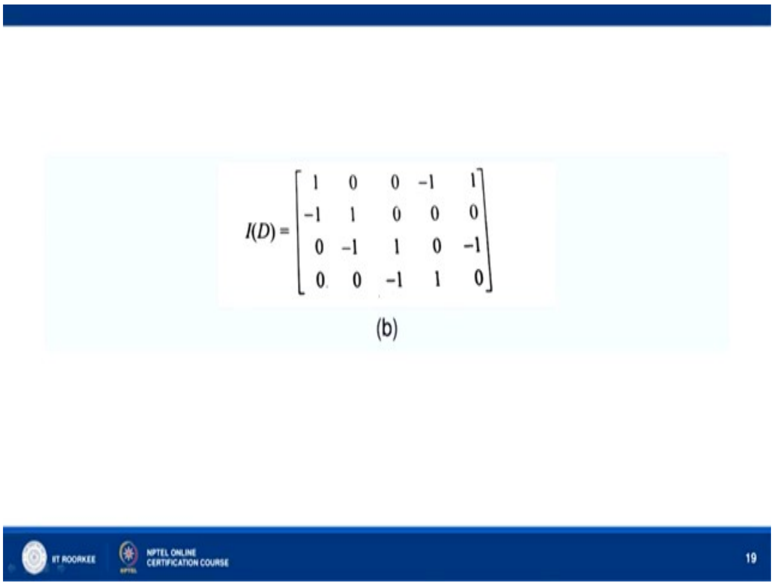

Then we have for this graph. This is a part and this one is (b) part. And (b) part we have 1, 0, 0, -1, 1; and then we have -1, 1, 0, 0, 0; and then 0, -1, 1, 0, -1. And then we have 0, 0, -1, 1, 0. So that is how we find the incidence matrix for the case of the two graphs. One is directed, the other one is…for the first (a) part which is undirected graph and for the (b) part which is a directed graph. So that is all in this lecture. Thank you very much for your attention.