Indian Institute of Technology Kanpur
National Programme on Technology Enhanced Learning (NPTEL)
Course Title
Error Control Coding: An Introduction to Linear Block Codes

Lecture-9C
Decoding of low density parity check codes-II: Belief Propagation Algorithm

by
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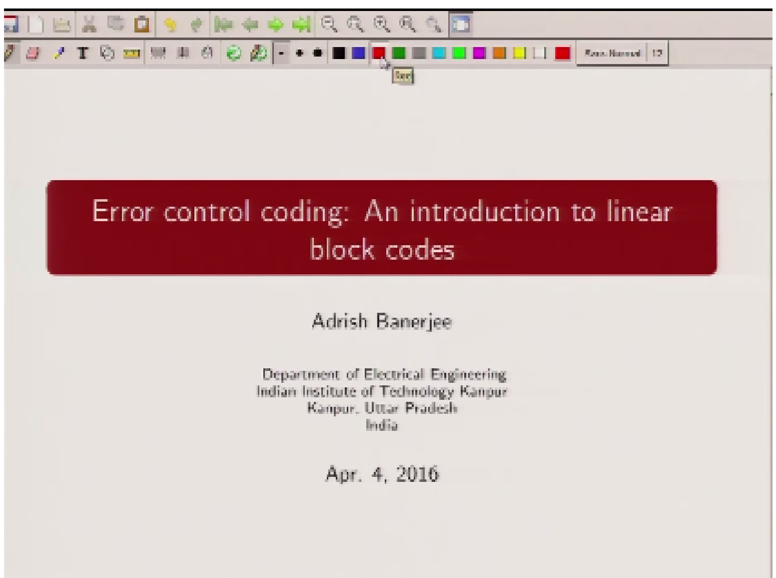

Welcome to the course on error control coding, an introduction to linear block codes.

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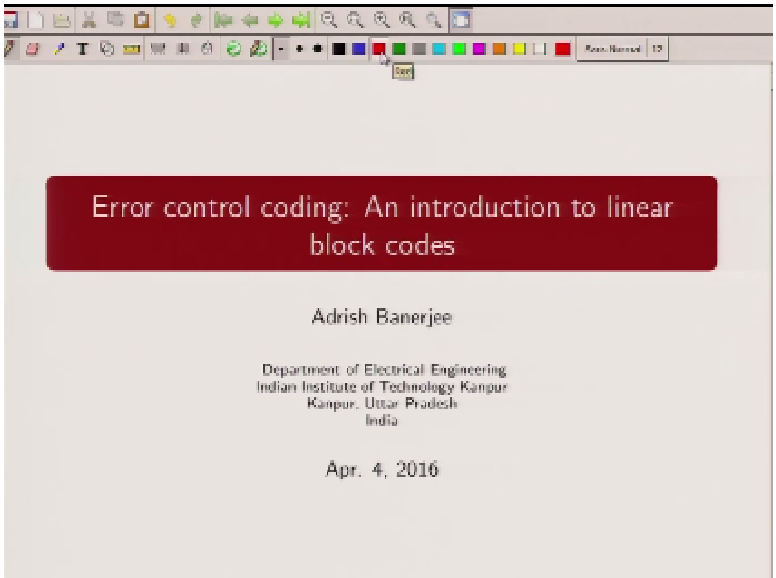

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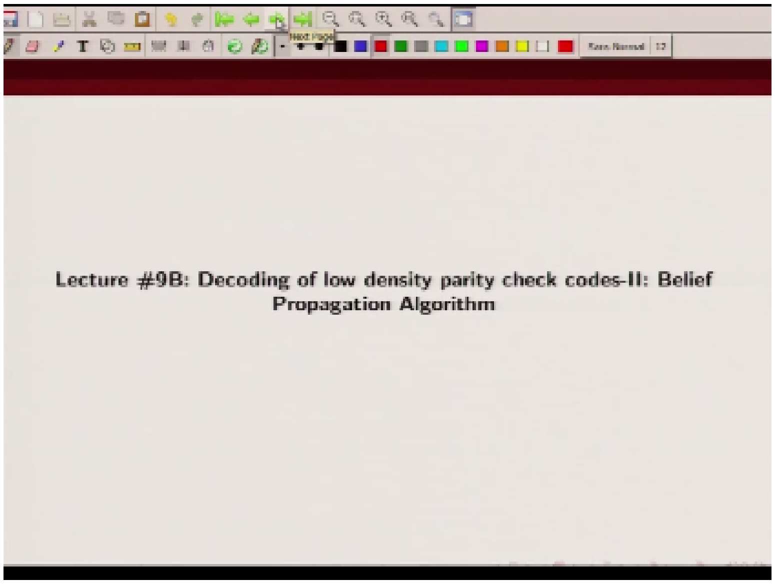

We will continue our discussion on decoding of LDPC codes. Today we are going to talk about probabilistic decoding algorithm.

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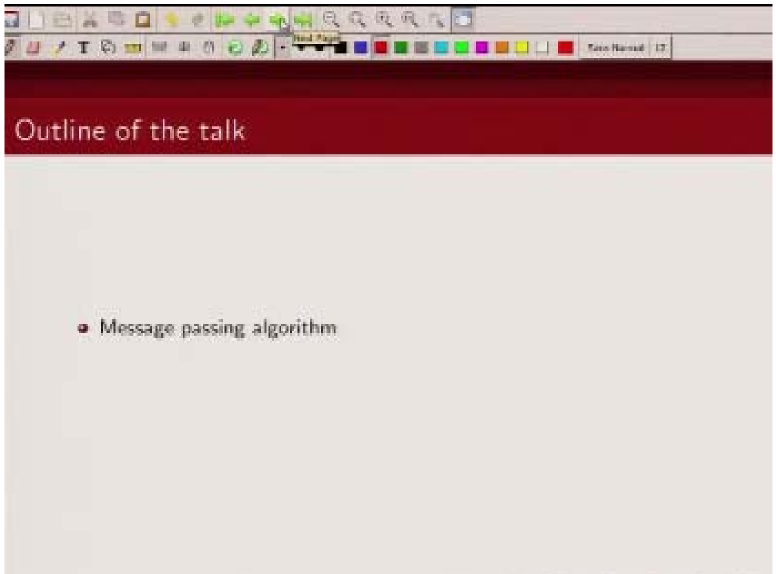

So we are going to talk about belief propagation algorithm.

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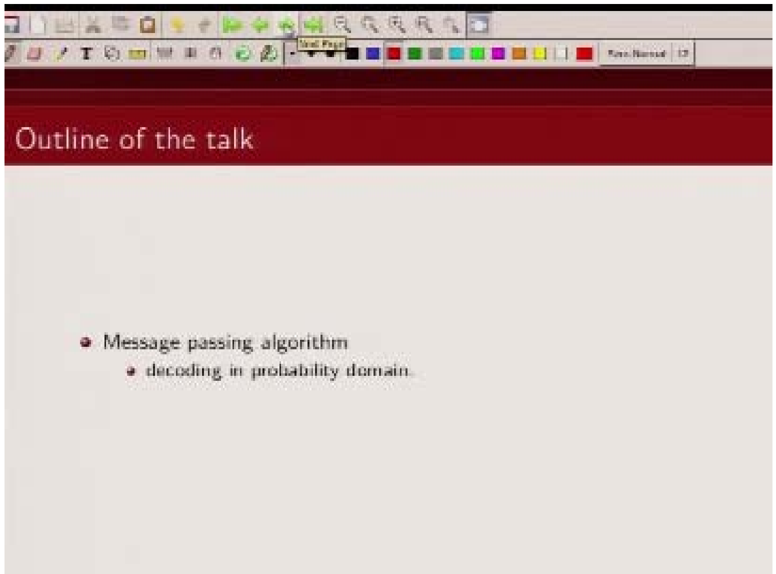

So before we do that we are going to prove some results and then use those results for decoding of LDPC codes.

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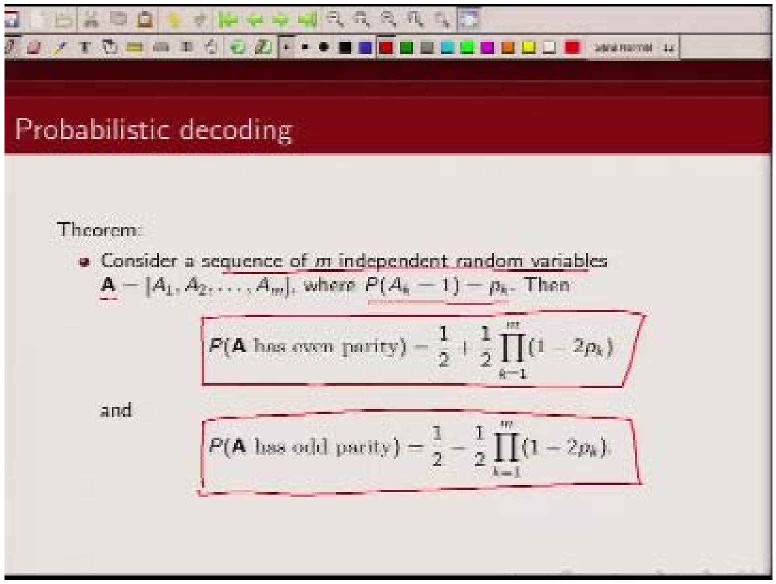

So we are going to use this lemma theorem to prove the decoding algorithm results. So what is this result which says if you have a sequence of m independent random variables which denote by A, So A_1, A_2, A_3,……..A_m are m independent random variables. And probability of A_k being 1 is given by P_k, then probability that A has even parity is given by this expression. And probability that A has odd parity is given by this expression. Now we will use, we will derive our expression for decoding algorithm based on these, this result. So let us first try to prove this result.

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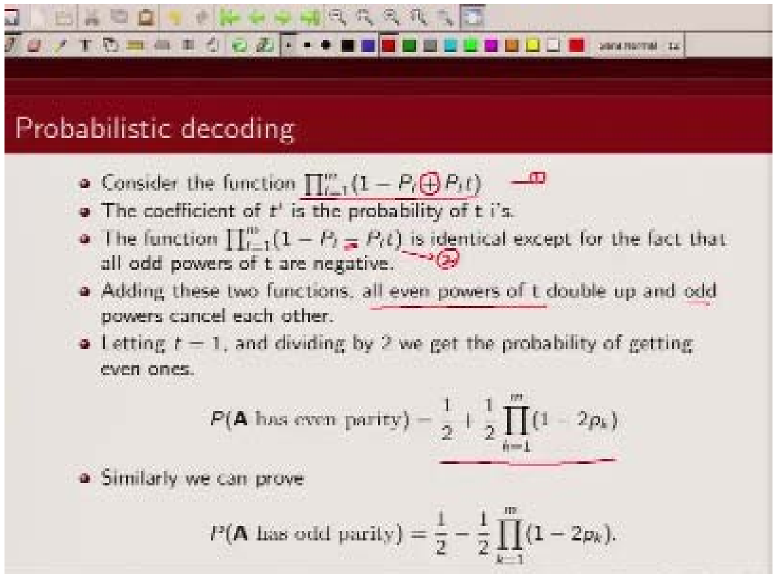

So let us consider a function of the form this $1-P_l+P_lt$, so if we look at the co-efficient of t here this will give us the probability of t i's. Now we can similarly consider this function where this is, this + has been replaced by – here. So this function is identical to this, except that the odd powers of t will be, have – in expansion. So if we expand this and we expand this, if we add both of them together what we will get is all the odd powers of t will go away okay.

So what we will be left with this even powers of t which are doubled up, and odd powers have cancelled out. Now if you put t=1 and divide by 2 we will get essentially probability that A has even parity, because we are left with only powers of t which is even.

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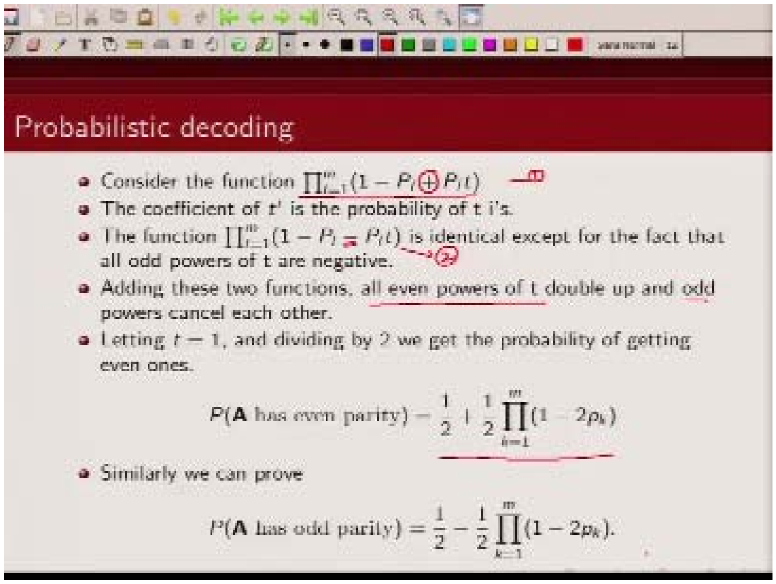

And similarly we can also prove probability that A has odd parity. Now in this case this will have all terms positive, odd powers also positive, this will have odd powers negative. So if we subtract this from this, we will get basically the probability of odd parity and that is basically given by this.

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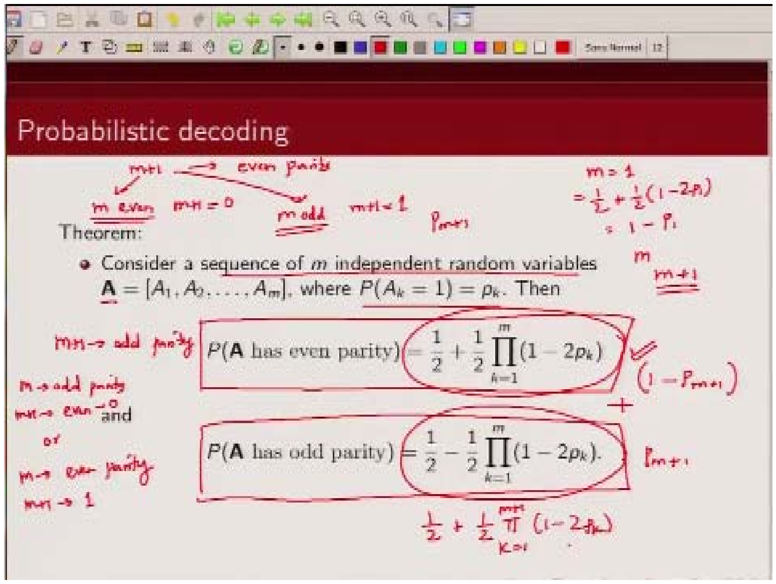

Now the same method can also be proved using mathematical induction. So if you want to prove it using mathematical induction let us just say we take m=1. If we take m=1 what do we get here, for m=1 we get basically ½ + ½ (1-2P). So this is nothing but 1-P_1. And what is P_1? P_1 is the probability, it is 1, so what is the probability it is even parity, it is 1-P_1. So this relation holds for m=1.

Now let us see it holds for also some m, then we have to show that it also holds for m+1. Now if it holds for m to show that it holds for m+1 we have to find what is the probability that sequence of m+1 independent random variables have even parity. Now when will the m+1 independent random variables will have even parity? They will have even parity when m of them have even parity and the mth bit that we get, mth with this 0.

Or some of m independent random variables they give odd parity and the mth bit that we receive is actually 1. So then we will get m+1 as even parity, so is it clear? So there are two cases, two ways in which we can get even parity when we are considering m+1 independent random variables. Either m of them had even parity and m+1 is actually 0, or m of them add up to odd parity and m+1 is also odd parity, okay.

So what is this probability of m being even, that is given by this. What is the probability that m+1 is 0 that is given by 1-P m + 1. What is the probability that m of them is odd, that is given by this probability. And what is the probability that m+1 random variable is 1, that probability is given by P times m+1. So the overall probability will be this multiplied by this plus this multiplied by Pm+1.

And if you simplify this we can show that this plus this will come out to be 1+1, K=1, m+1 1-2P_k. So details of the calculation I am just leaving it, but this is how using mathematical induction we are going to prove that this also holds true for m+1 and hence proof. Similarly we can prove that probability that A has odd parity is given by this expression. We will first show that for m=1 this is nothing but P_1.

So that it holds true for m=1, assuming it holds for m then we have to show it also holds for m+1. Now for m+1 to have odd parity 2 ways, m has odd parity and the m+1 bit that we get is even parity is 0 basically is 0, or m has even parity and m+1 bit that we get is actually 1. So similar to this case we can also find out these probability and if we add them up we can show that this will be equal to half minus half product from k= 1 to m+1 of this, so we can say that P(A) has even parity is given by this and P that A has so some of these m random variables have odd parity is given by this, so these are the crucial expressions that we will be using in our decoding algorithm.

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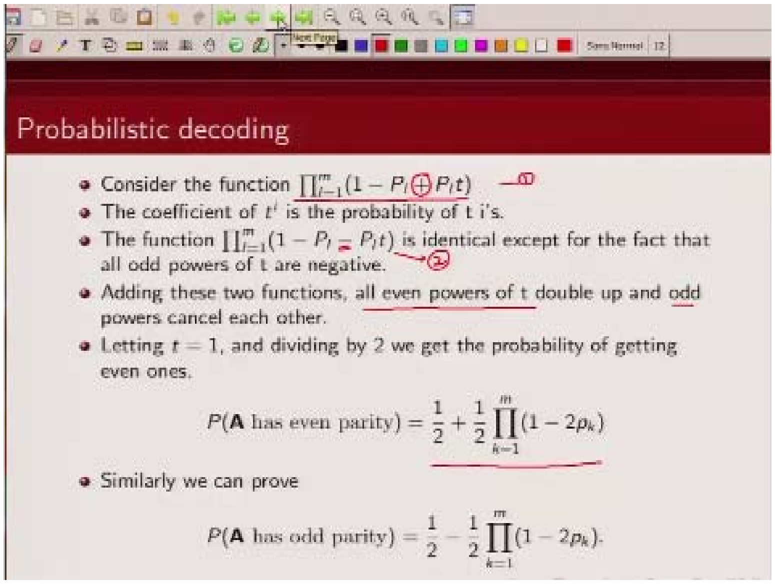

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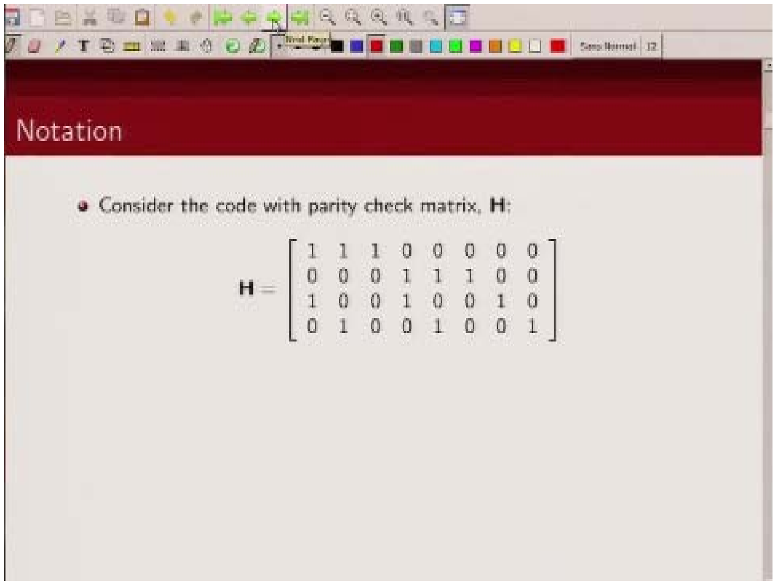

$$\mathbf{H} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix}$$

So let us consider an example, so this our parity check matrix we

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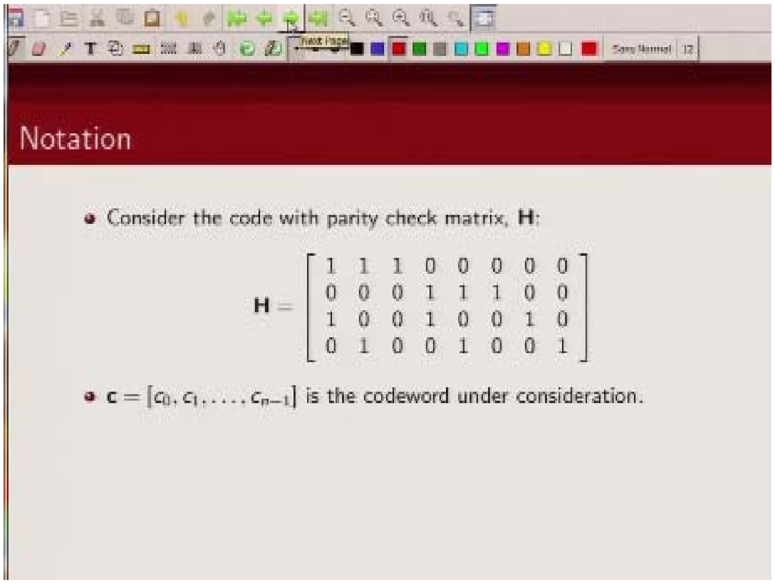

Will first describe the notations that we are going to use and then we will state the decoding algorithm and the corresponding equations and then we illustrate using one example.

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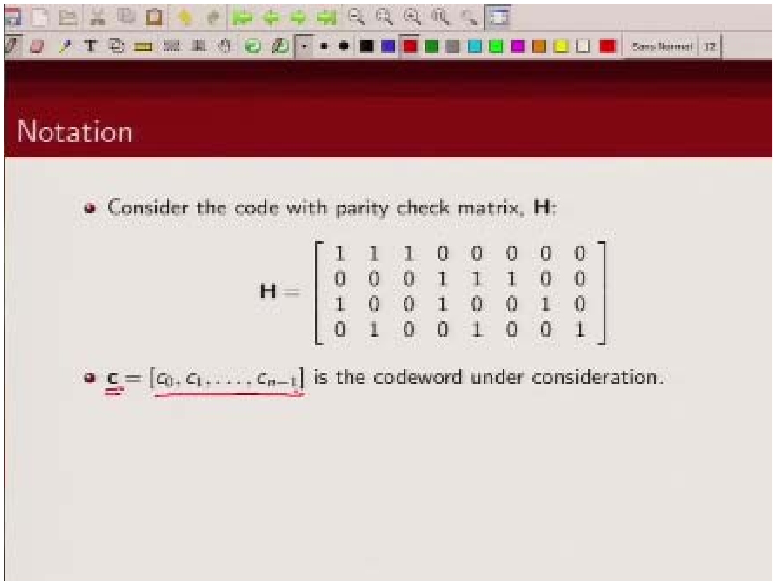

So we are using c to denote our code word, so this is an n bit code word, C_0,C_1,C_2,C_n, that is our code word .

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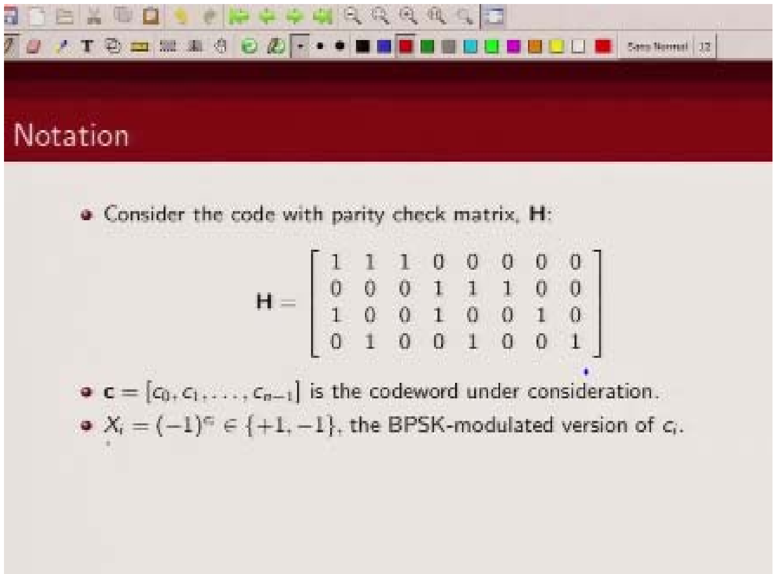

Now

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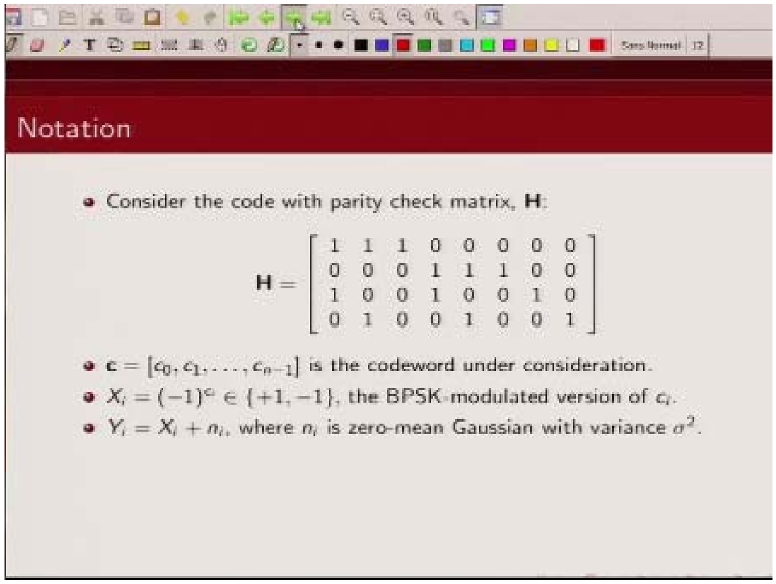

This code word is modulated using BPSK modulation so we are mapping 0 to1 we are mapping to -1, so that is your BPSK modulated version of the code bits denoted by X_i

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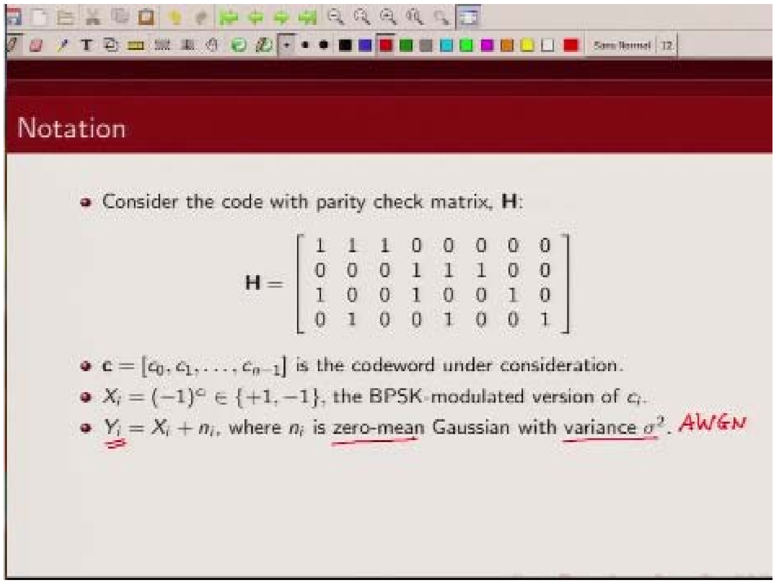

Yi is your received modulated code word so this is we are considering an additive white Gaussian noise channel with noise variance given by n^2 and this is zero- mean Gaussian noise

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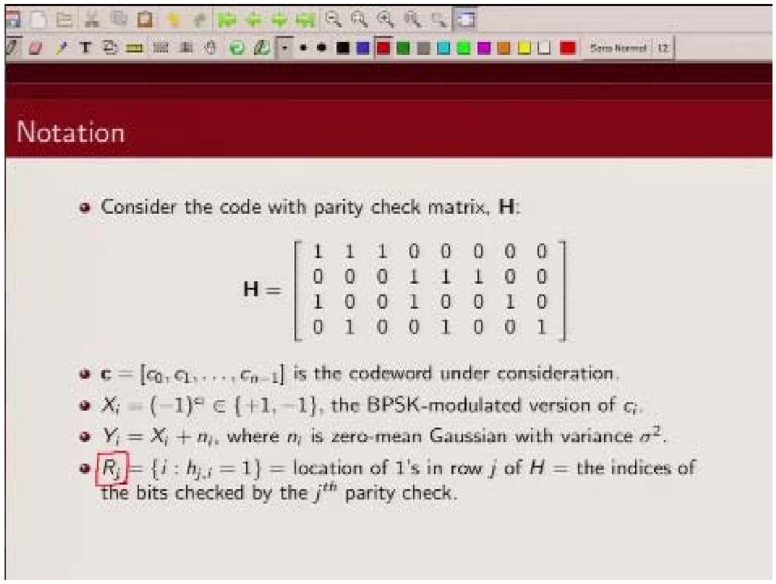

We use this notation Rj to denote the location of 1's in row j. Now what does location of 1's in the rows of the parity check matrix denote? It denotes the bits that are participating in the parity check equation, so let us take

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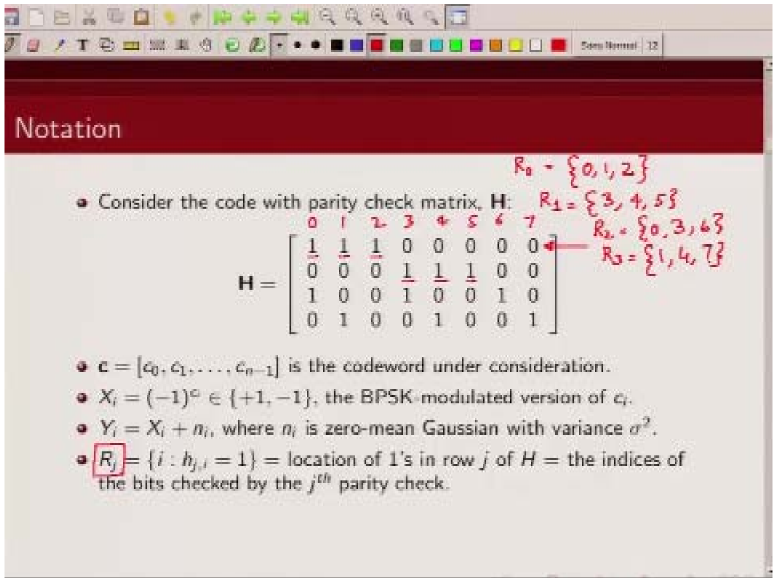

This example, what is R_0, now R_0, so what are, so R_0 correspond to the 0^{th} row which is this row. Now look at the bits that are 1 here 1,2,3 these are bits which are 1, so R_0 corresponds to let us just label them 0,1,2,3,4,5,6, so R_0 corresponds to 0, 1, and 2 and what does it mean, it means for the first parity check equation the bit number 0, 1, and 2 are participating. Similarly R_1 will be this, this, this, so R_1 will be 3, 4, and 5, R_2 will be 0, 3, and 6, and R_3 will be 1, 4, and 7, so that is your R_j

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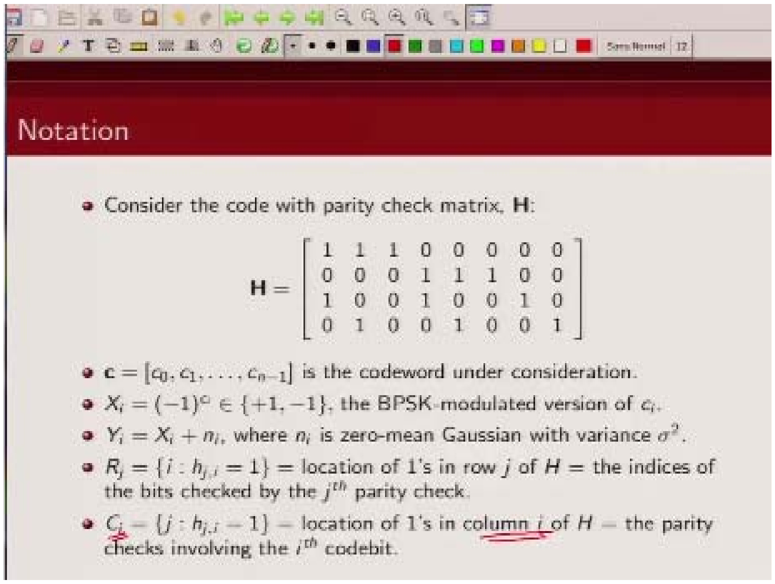

Now we use this notation C_i to denote the location of 1's in column I, now what does location in column i denotes?Itt denotes that, that i^{th} bit it participating in how many parity check equation, which parity check equation, so let us

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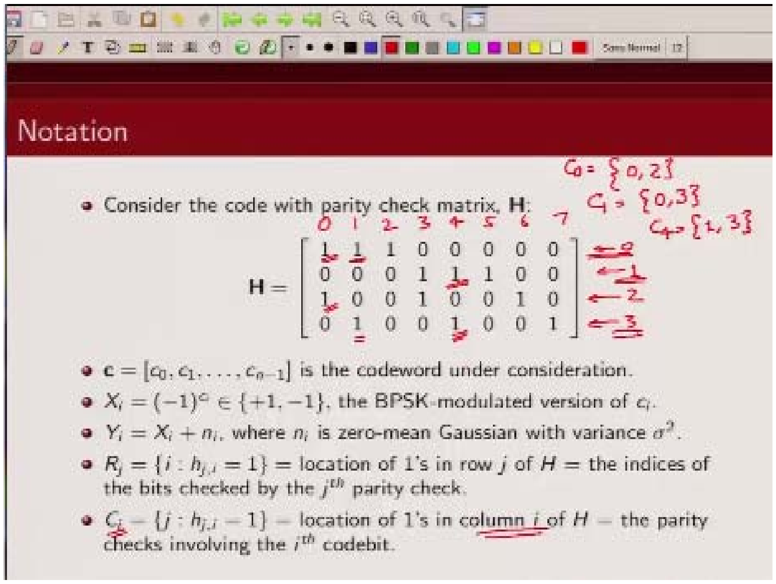

Look at what is C_0, so this was again 0, 1, 2, 3, 4, 5, 6, 7. So C_0 is what, C_0 is again this is just call it 0,1, 2, and 3, so this 0^{th} parity check equation 1, 2, and 3, so bit number so if we look at column 0 so you can see this bit is participating in 0^{th} parity check equation and second parity check equation C_0 will be 0 and 2. Similarity C_1 is going to be 0 because it is participating in 0^{th} parity check equation and 3 okay, you can take any let us take C_4 what is C_4, 4^{th} bit is participating in parity check equation 1 and participating in parity check equation 3 so like that you can find out what is C_i, fine?

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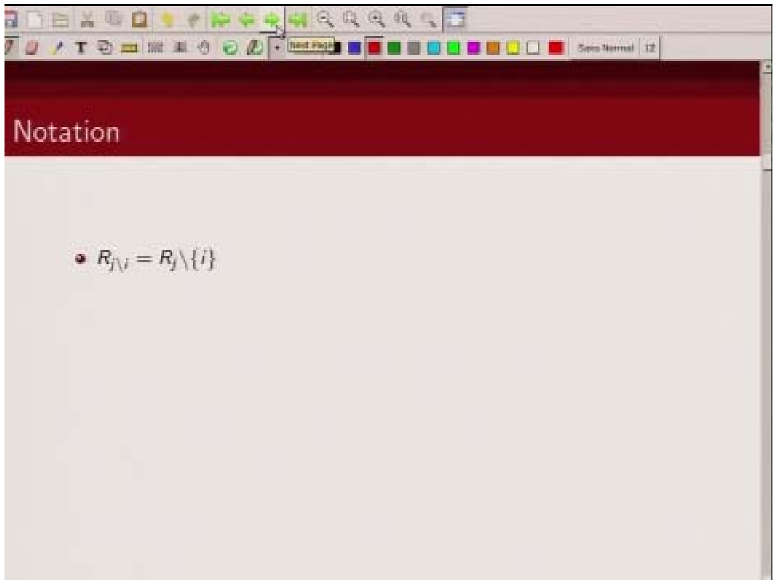

Now we define this set R_j- a particular element i so

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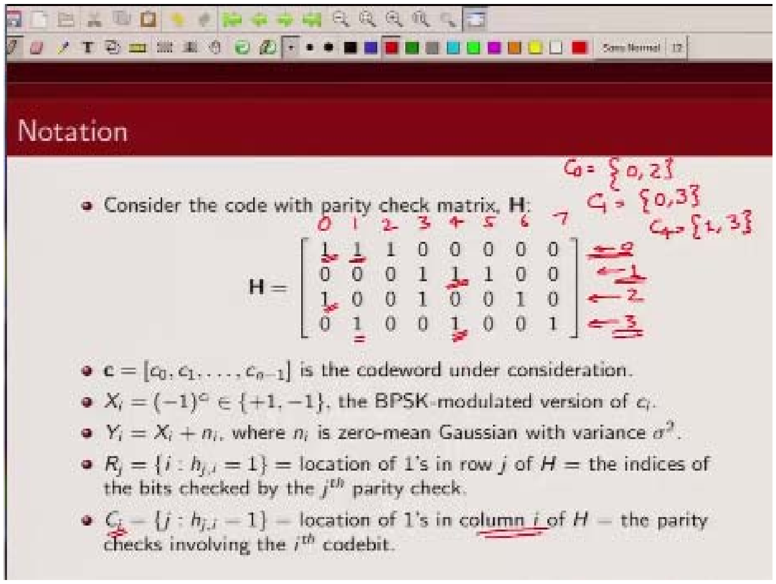

Let us go back, so what was our R let us say R_0 what was R_0? R_0 was location of 1's in 0^{th} row, so that location was 0, 1, and 2, right, so if

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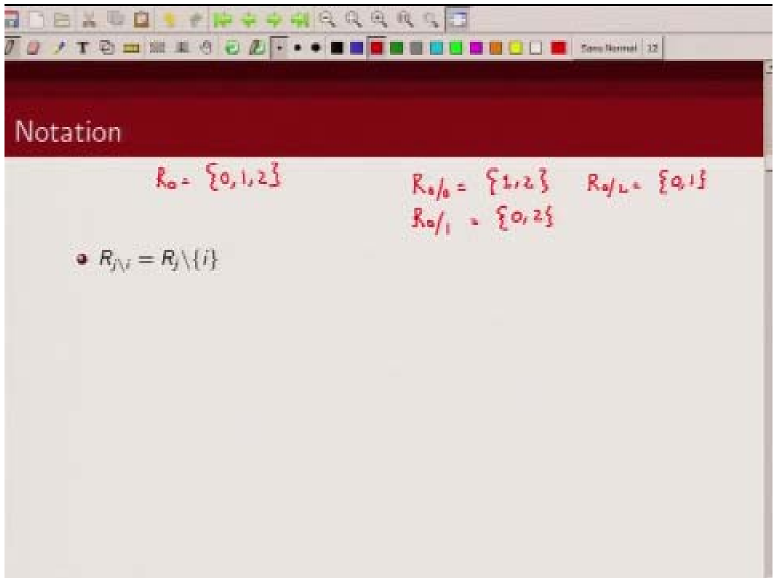

I define let us say R_0 / $_0$ that would be then because R_0, R_0 is what, R_0 is 0, 1, 2, so R_0 – 0 will have 1 and 2. Similarly R_0 -1 this will be set containing 0 and 2, and this will be set containing 0 and 1.

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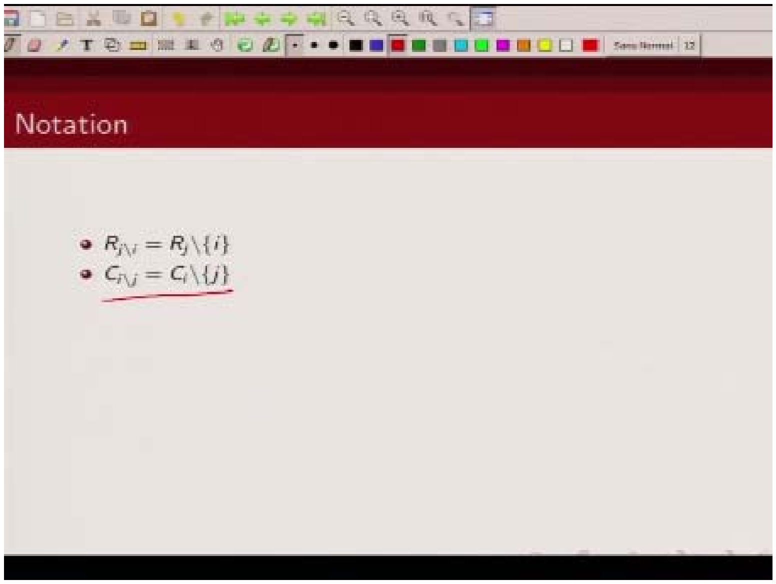

Similarly we define the set C_i – this element j so for example

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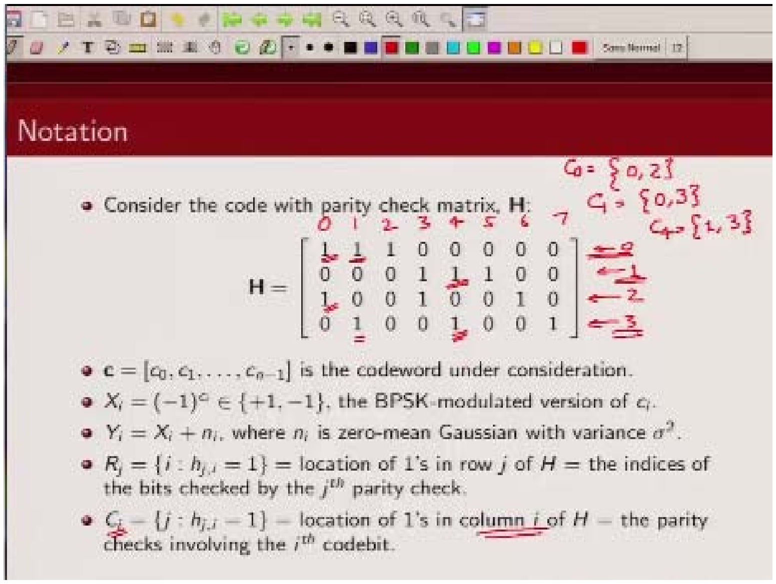

In this case let us say C_1 is 0 three

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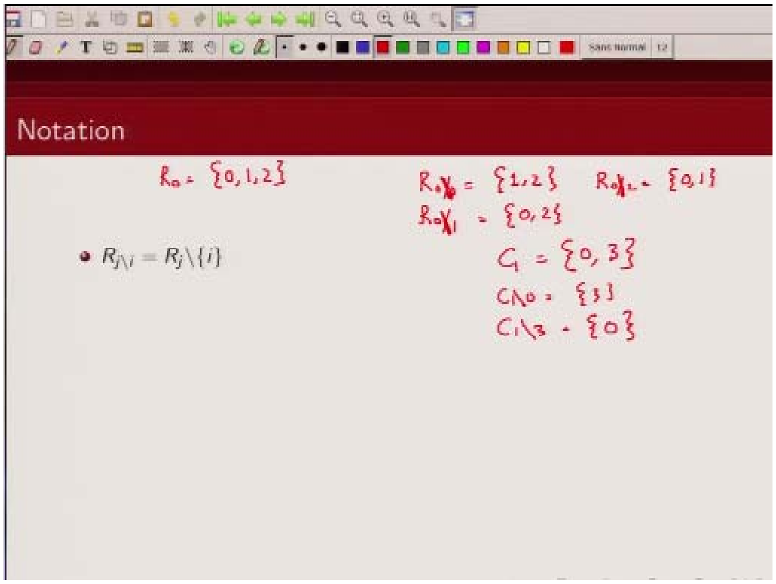

So C_1 has element 0 and 3 so if we define this, this notation is like this, this is this 0 this will be 3 or C_1 will be 0 okay

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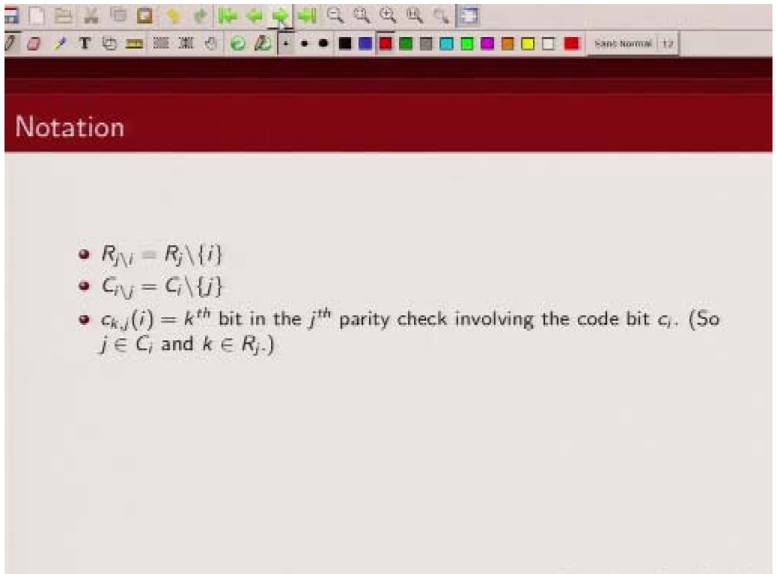

Now we defined

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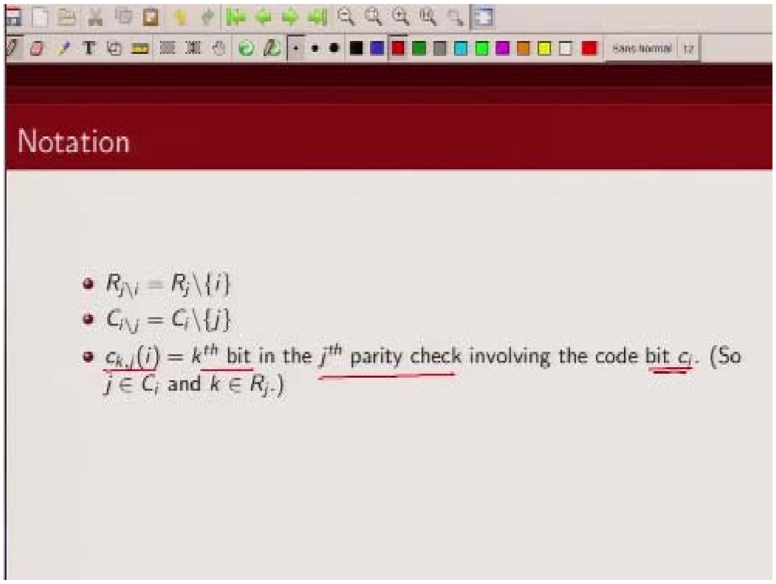

by $C_{k,j}$ the k^{th} bit in the j^{th} parity check equation involving code bit c_i, that is denoted by $c_{k,j}(i)$

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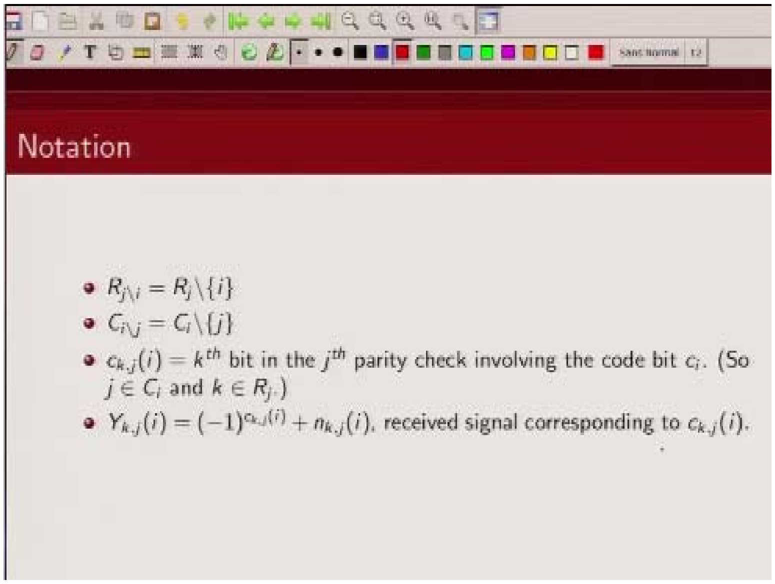

So the received sequence corresponding

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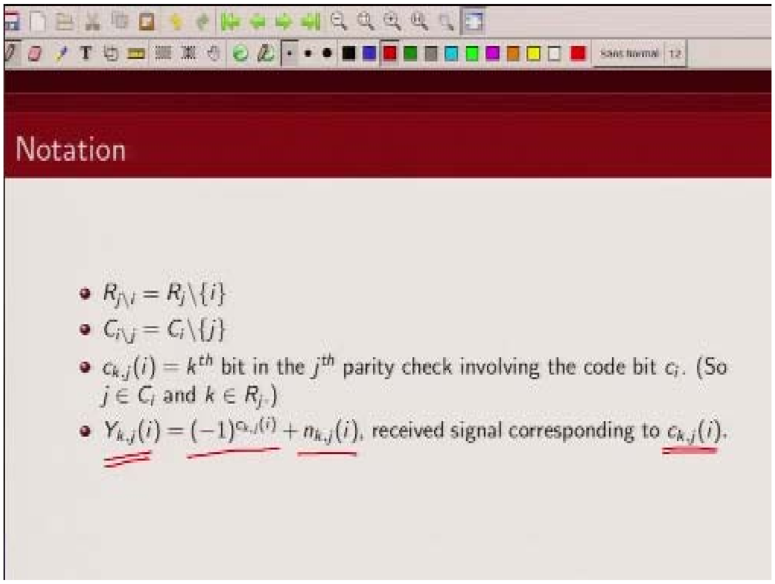

To this transmitted sequence would be then is the modulated version and this is the noise added. So this is the received signal corresponding to this code bit.

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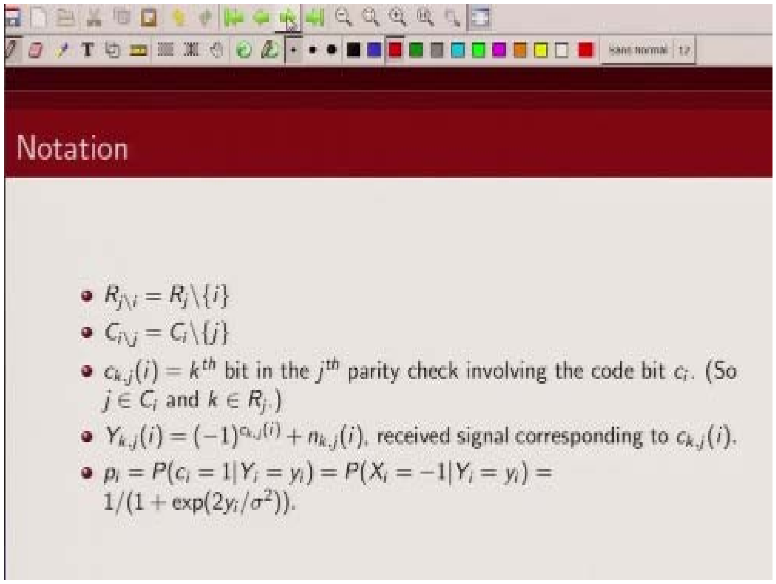

Now for an AWJN channel we can compute this probability

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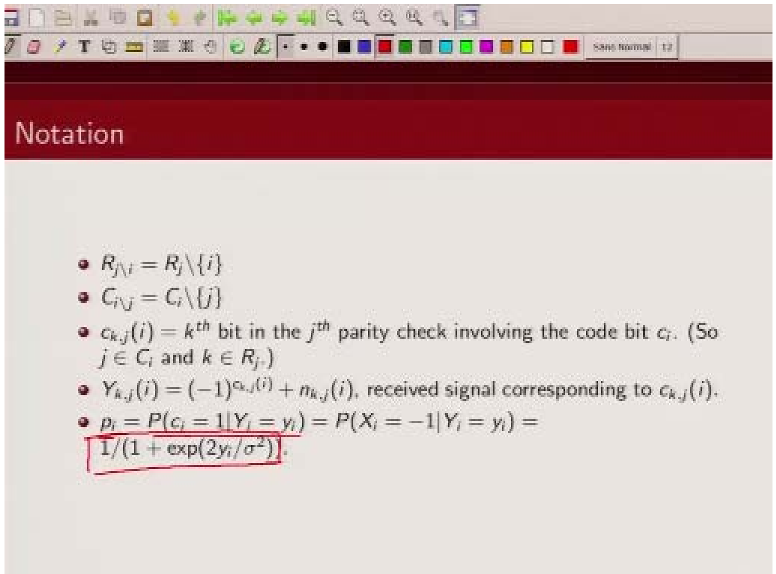

That $P(C_i = 1 | Y_i)$, this can be given by this expression

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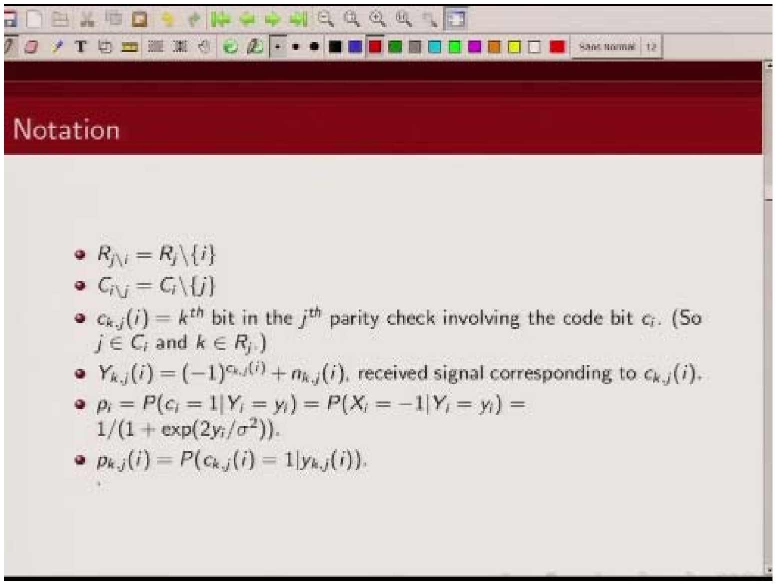

And we denote by

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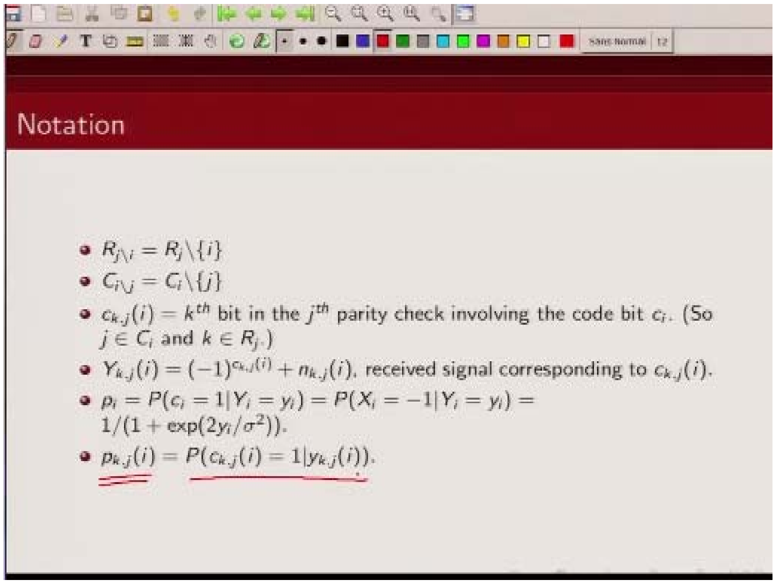

$P_{k.j}$ the probability that $C_{k.j}$ is 1 given a received sequence $Y_{k.j}$

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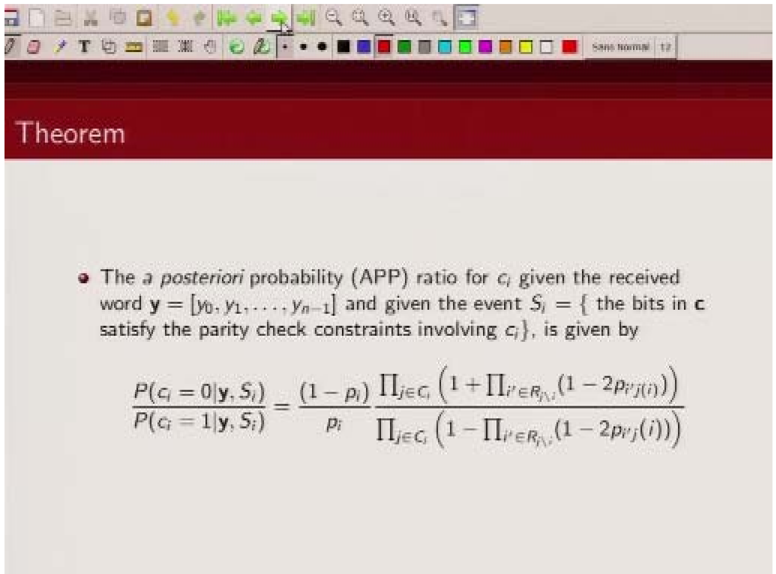

So then we can write down the expression for a posteriori

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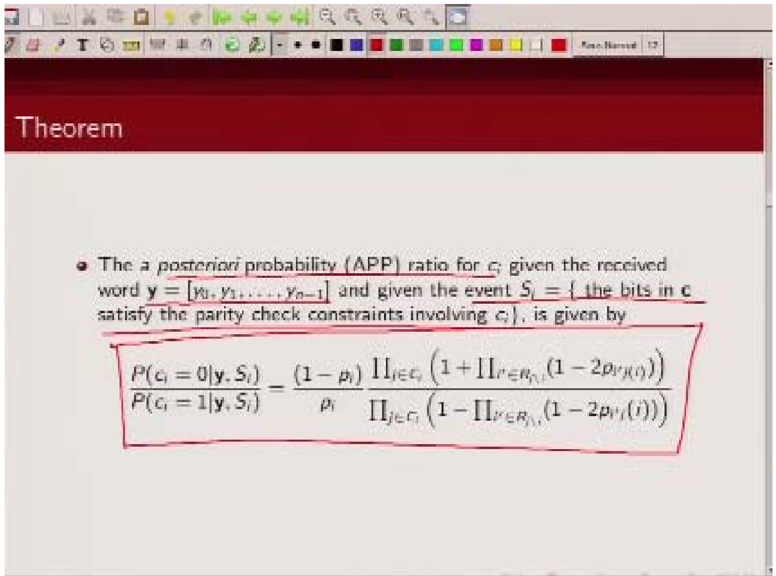

Probability of our code bit C_i given our received sequence is y and given that the parity check constraints containing C_i has been satisfied. So what is the probability of C_i being 0 given a received sequence Y and given that the parity check constrain containing involving C_i has been satisfied. This is given by divided by probability of C_i being 1 given Y and S_i, this expression is given by this expression, and we are going to use the theorem that we have proved in the beginning of the lecture to derive this expression, namely if you have m independent random variables what is the probability that some of them has even parity and some of them, some of them have odd parity, we are going to make use of that result.

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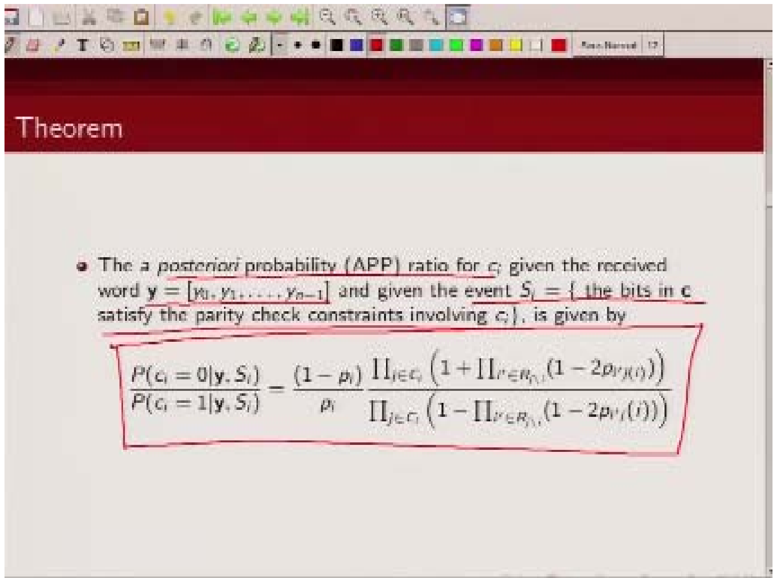

To derive this expression.

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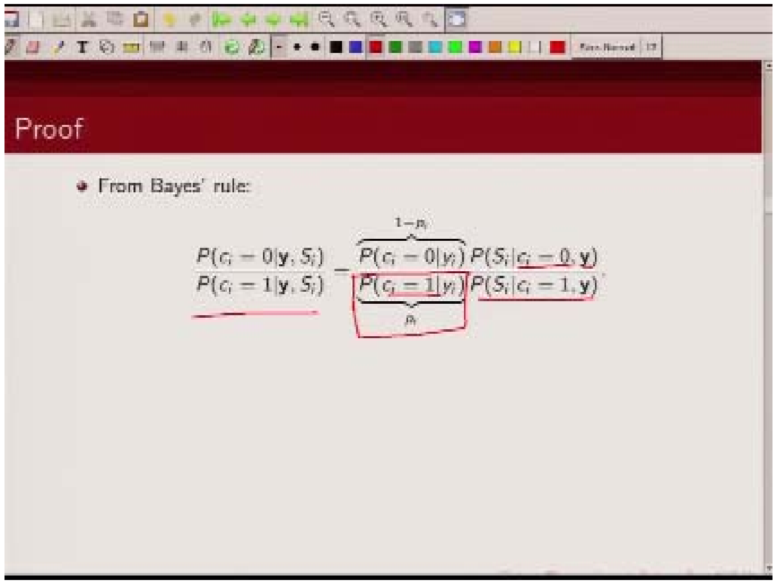

So let us see, so from base rule we can write this probability as probability of C_i being 0 given Y_i, multiplied by probability that the parity check constraints are satisfied given C_i is 0 and the received sequence is Y, and similarly a denominator we can write, that is probability of C_i being 1 given receive sequence Y and multiplied by the probability that parity check constraints are, involving C_i is satisfied when C_i is 1 so this, this probability is nothing but our P_i.

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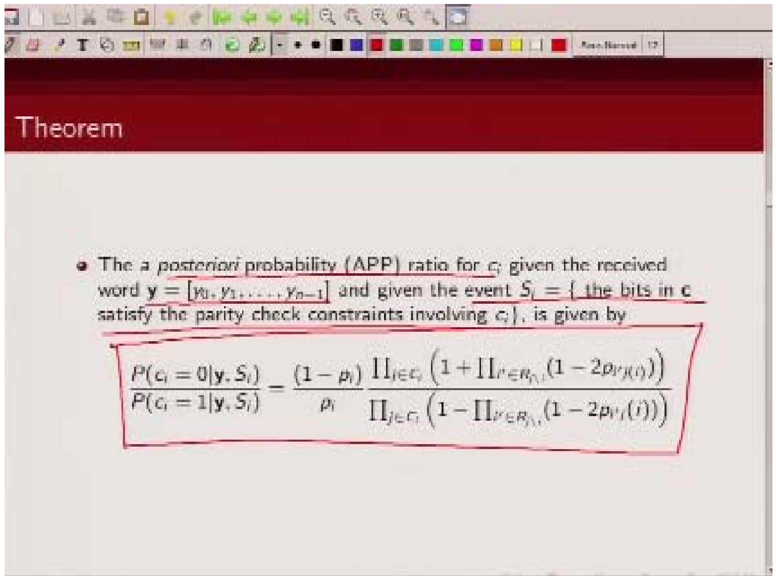

To go back.

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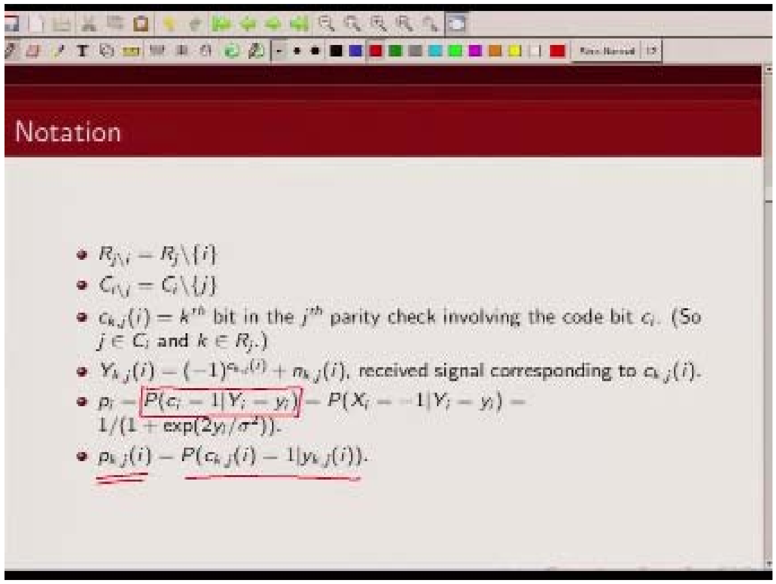

What was P_i, P_i is probability of C_i given V_i so that is P_i.

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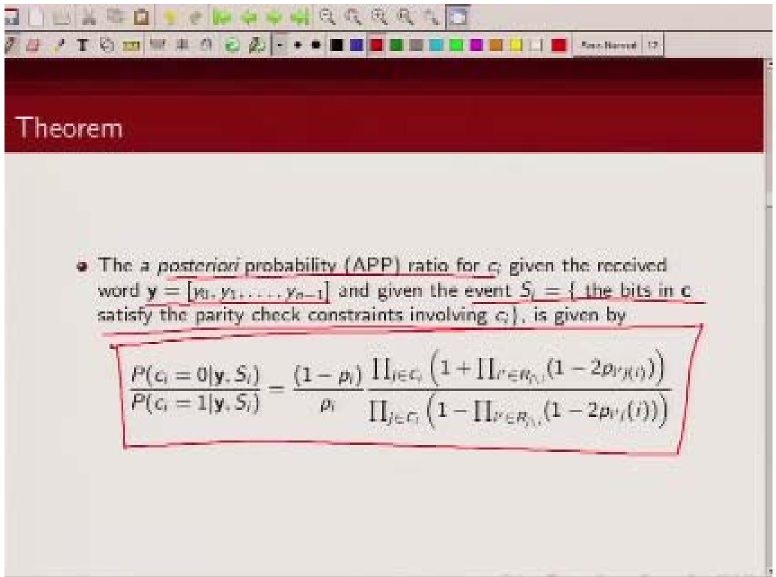

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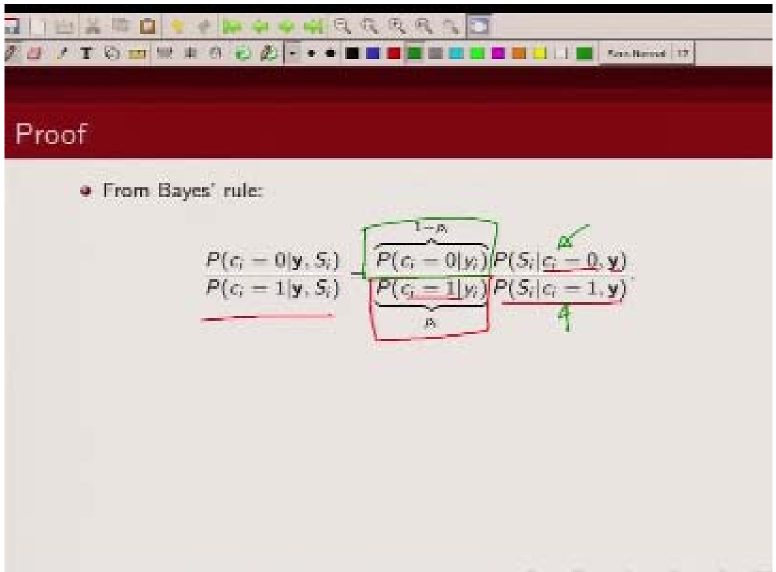

So then this with, this upper term would be 1 – P_i okay now let us pay close attention to these terms then.

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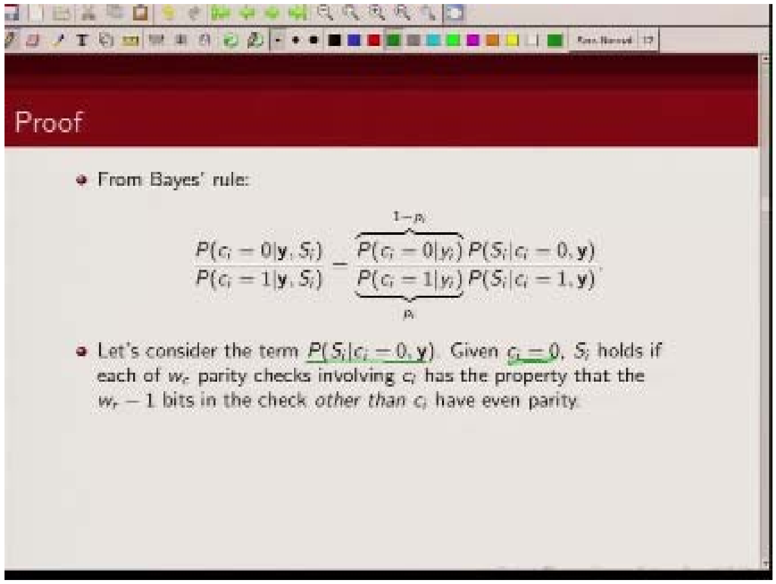

So what is this given that my code bits C_i is 0, when will parity check constrain involving C_i will be satisfied? It is when sum of other parity bits involved in the parity check constraints they add up to have even parity right.

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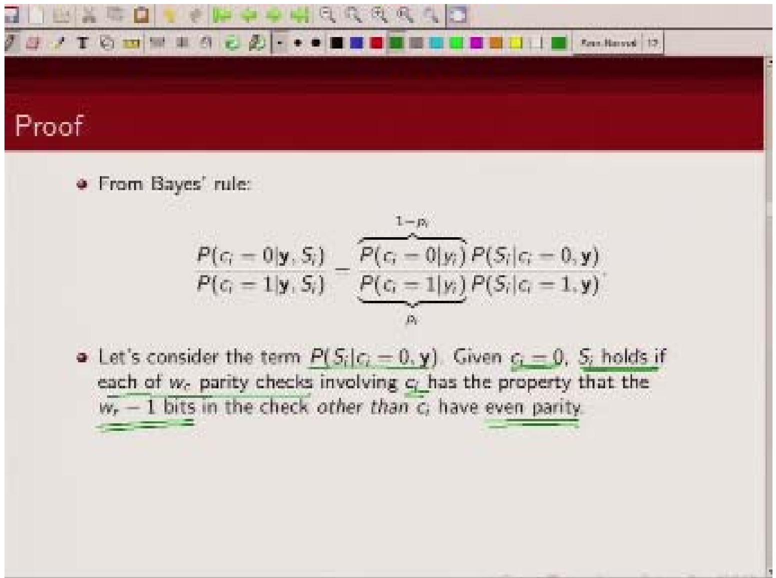

So this even C_i will be satisfied if each of these parity check equations where C_i is involved other than this C_i bit if all other bits involved in the parity check equation in case of us regularity Pc code that number is wr – 1, if those all those bits have even parity because Ci has Ci is 0 so the other bits should have even parity then only the parity check equation involving C_i will be satisfied, so we need to find the condition that sum of other parity check bits involved in the parity check equations where C_i is participating they should have even parity.

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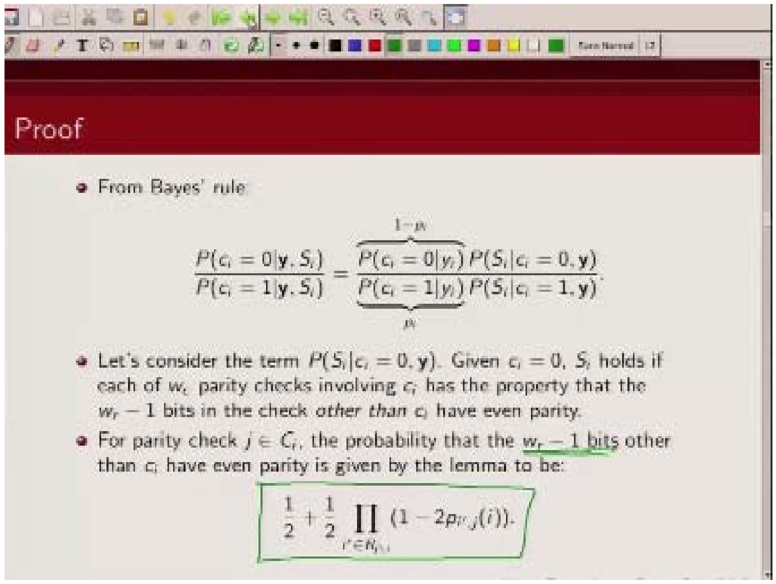

Now from the theorem that we have proved we know what is that probability, probability that other than C_i wr – bits they have even parity, that probability is given by this expression, if you go back.

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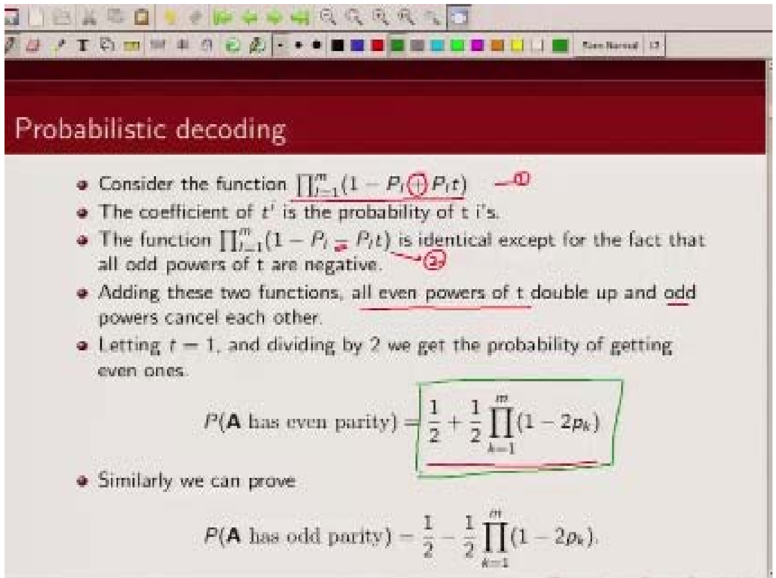

Probability that they have probability that m random variables have even parity is ½ + ½ product 1 – 2pk, so probability that wr – 1 bit.

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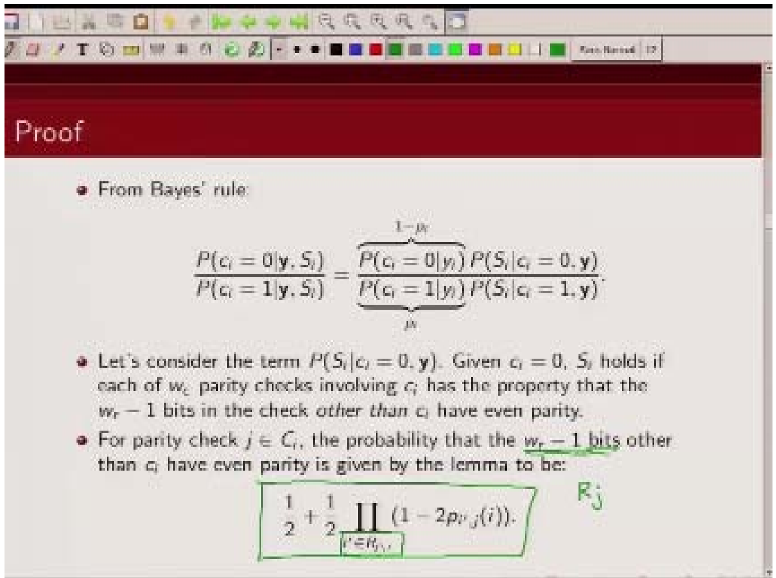

So ½ +1/2 now pay close attention to this, this 1- 2pk now what are the bits that we are considering, now what will R_j tell us, R_j will tell us the Gr parity check equation.

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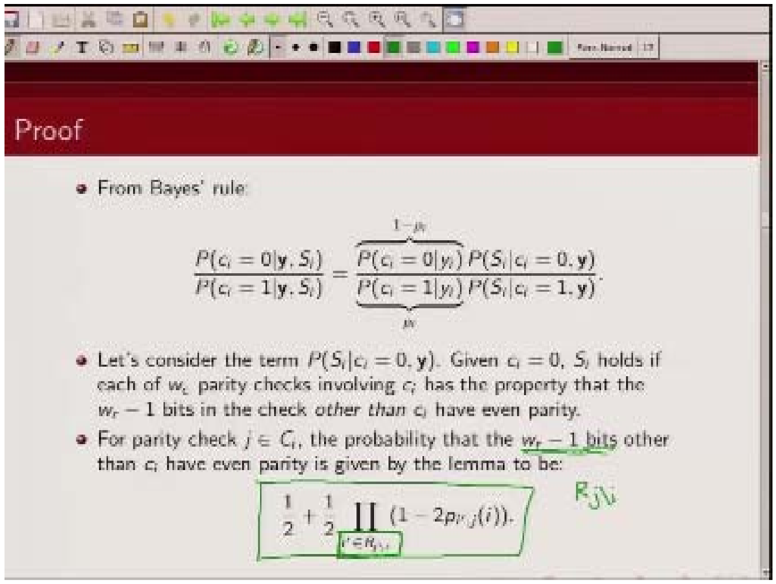

And R_j – I where I is, C_i bit is involved and this is –i, so the other bits other than Ci which are participating in the parity check constrain product of this, I mean they should add up to have even parity so this is a set where C_i is participating in a parity check constrain, so other than C_i, other bits have even parity that is captured by this particular set.

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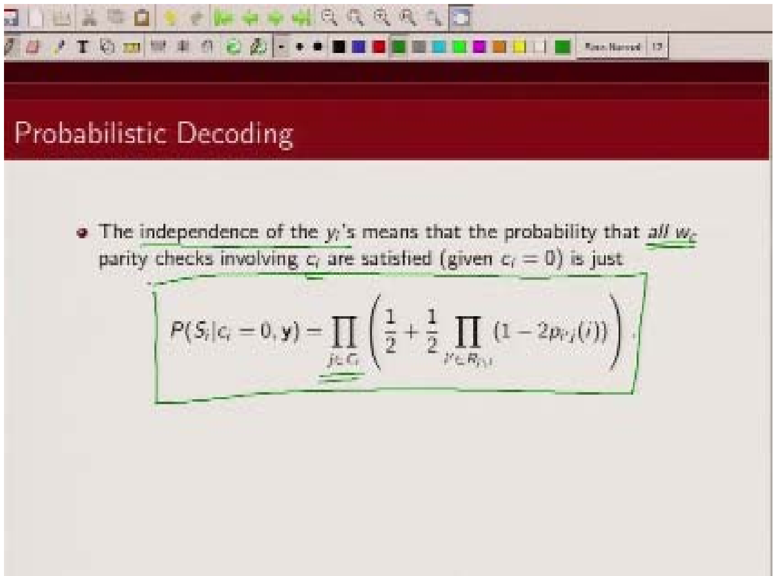

And this should hold for all parity check equations involving C_i so this should be hold for all w_c parity checks sets where this particular bit C_i is participating, so that is why you assuming that why i^s are independent I can then write the probability as product over all such parity checks equations where this is involved, so I can write down then probability that my parity check set constrain is satisfied given C_i is 0 is given by this expression.

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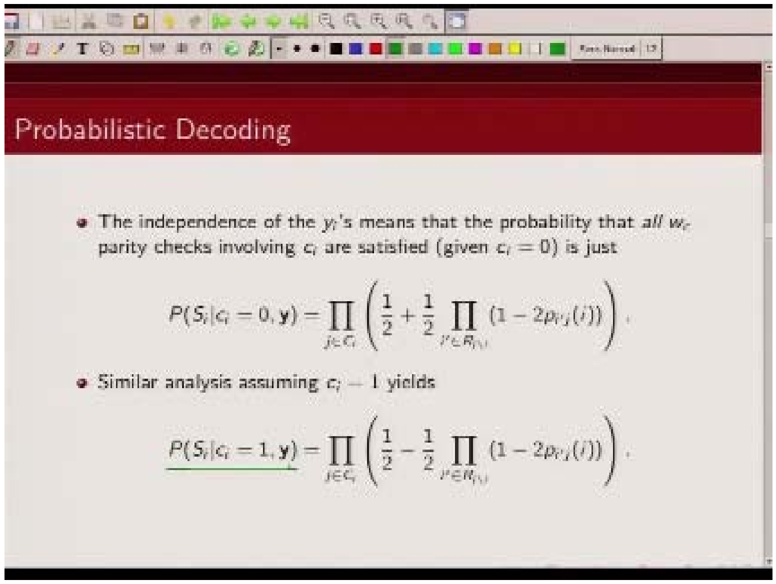

And I can follow the same logic to find out the probability when C_i is 1, when C_i is 1 what I want the other bits should add up to have an odd parity and that is.

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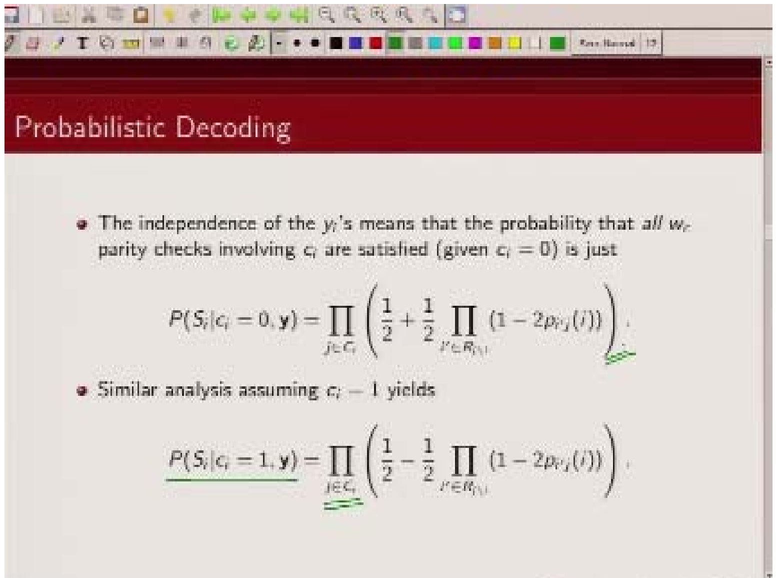

Given by this expression and this should hold for all parity check, w_c parity check equations so this is assuming independence I can multiply by each of these probabilities, so this is the probability of this parity check set, I mean parity check constrain getting satisfied when C_i is 1 and this is the expression when C_i is 0. So if I plug these values.

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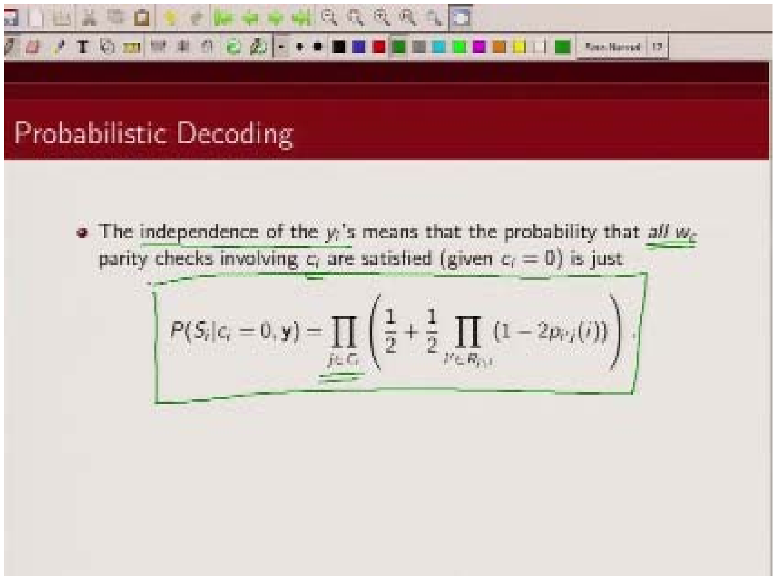

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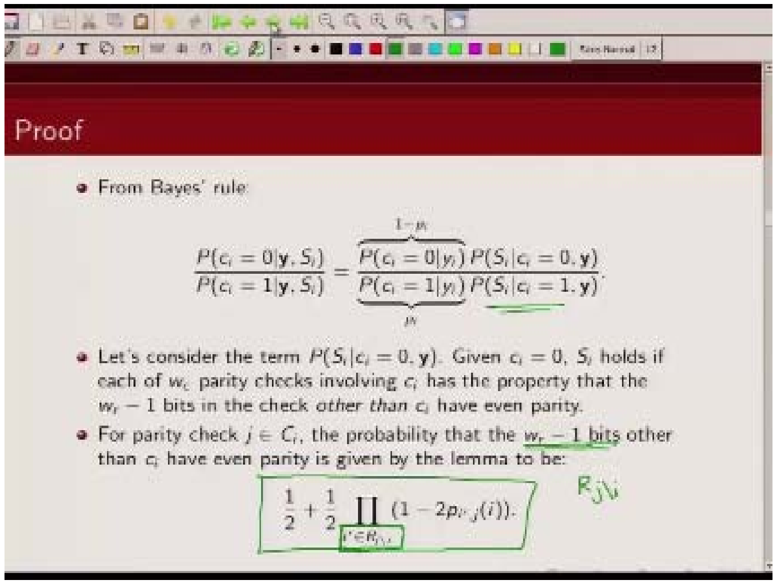

In my expression here this expression what I get is.

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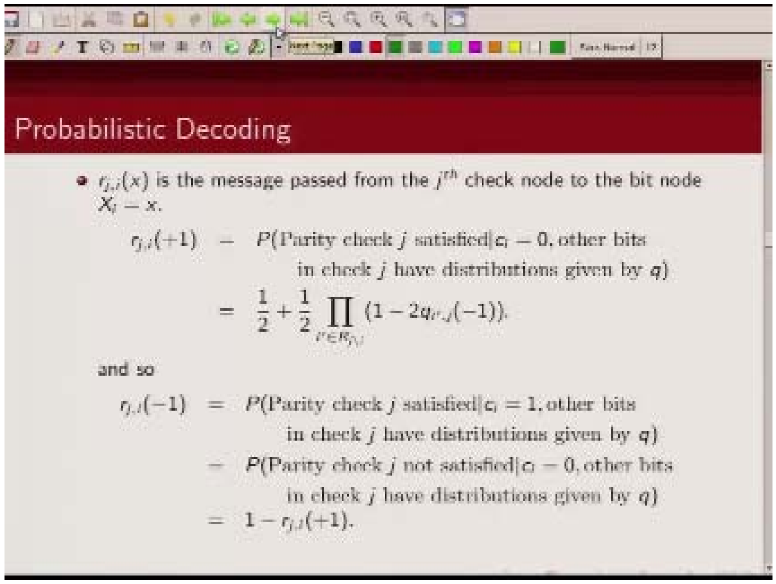

The expression for.

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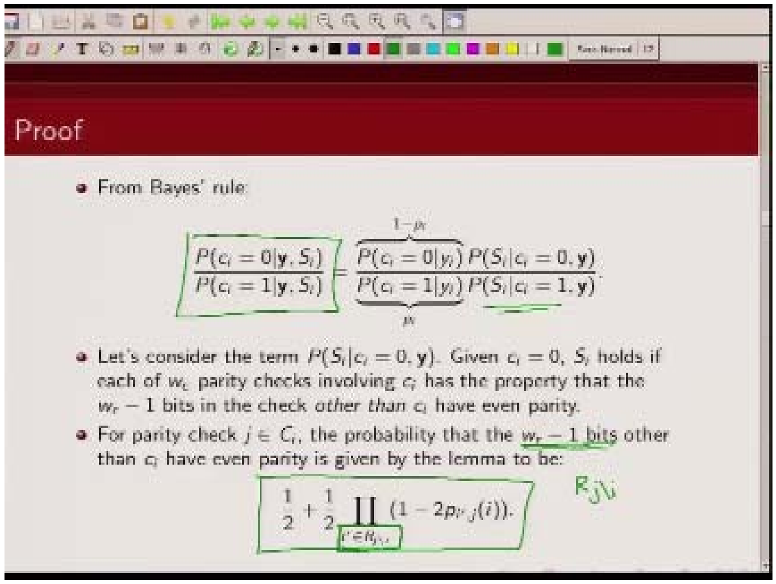

This, okay.

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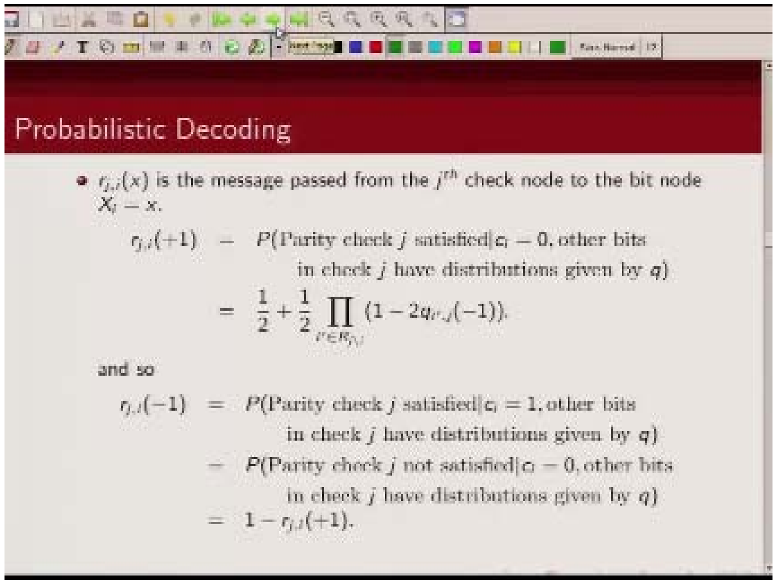

So as we have said before we are writing, we are representing this LDPC code using this stenograph and there are 2 types of information which are getting propagated. One is one sort of messages which is from the message notes going to the variable, going to the parity check notes and this one set of message which from the parity check notes coming back to the message notes.

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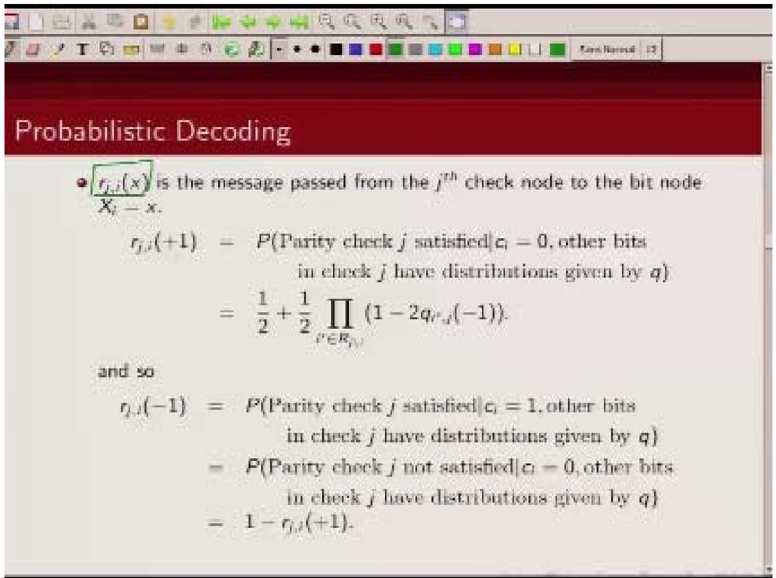

So we are denoting by R_{ji} the message which is passed from j parity check note to the i^{th} bit, we are denoting this by Rji so what is r, Rji is the probability that j^{th} check note is satisfied given x is + 1, so this is a probability that j^{th} check note is satisfied given C_i is 0 and other bits are given by distribution given by this q, now what is this q distribution?

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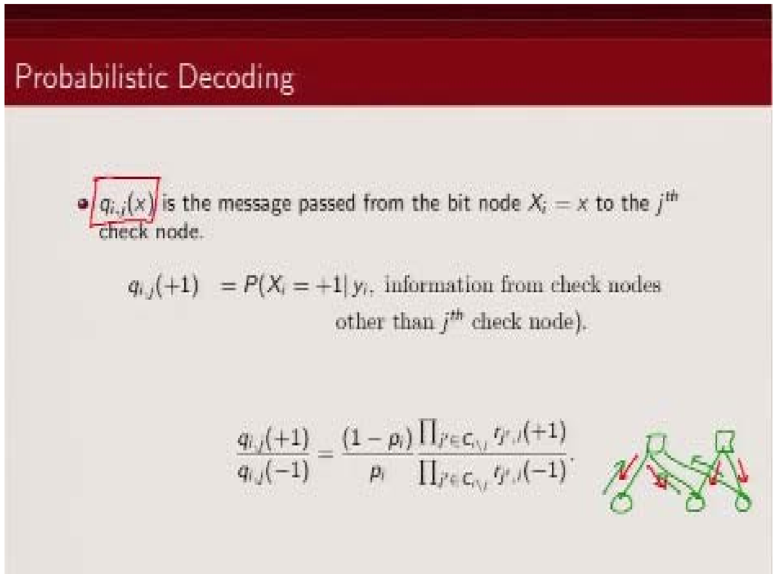

We will come to so that 2 type of messages, as I said there is one message so if I draw any tanner graph let us say just draw any tanner graph, let us say this some graph I am drawing, so there is one set that matches it which is going from message to this check nodes okay this is one set of messages which are going like this and there is another set of messages which is coming from the check node to the message bits. So we are denoting by q_i the message which is passed from bit node i to the j^{th} check node.

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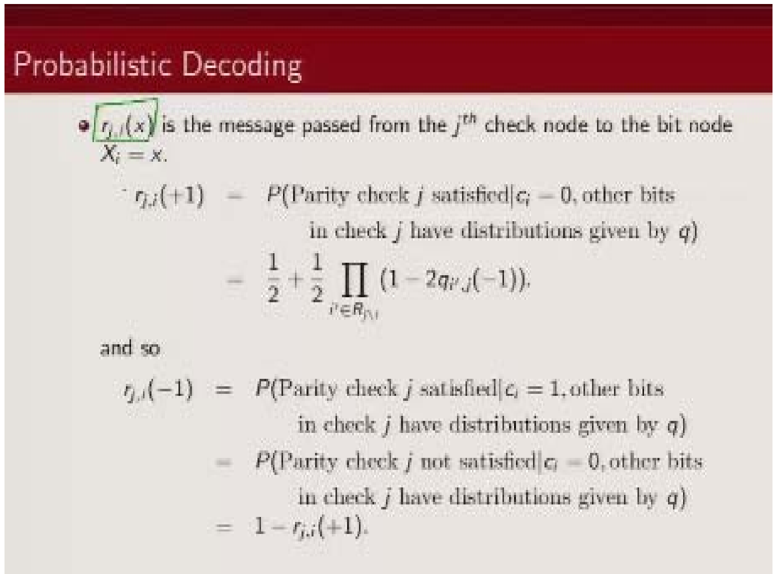

And we are denoting by $r_{j,i}$ the message which is passed from the check node to the bit node, now probability of this being.

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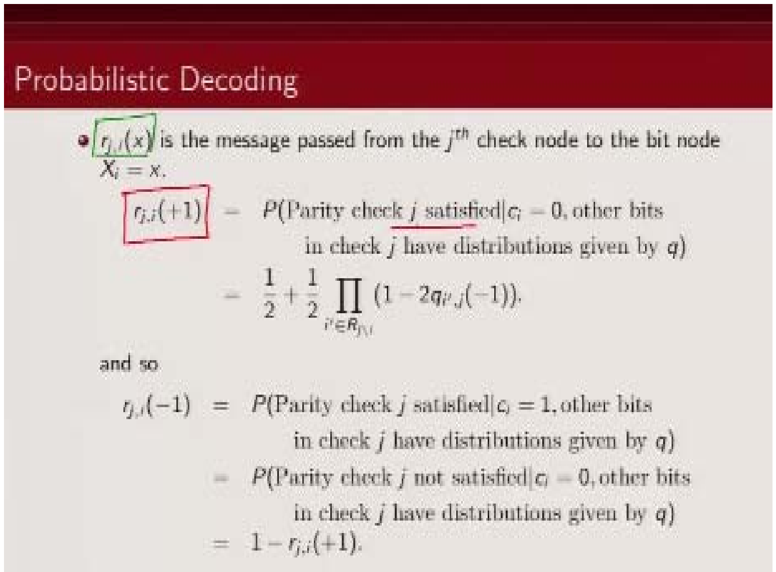

X being +1 which is basically correspond to c_i their code bit being zero, this is this probability is defined as what is the probability that j^{th} parity check constrain is satisfied given that c_i the i^{th} bit is zero and other bits are given by distribution given by q_i. Now what is the probability that j^{th} parity check constrain will be satisfied given c_i will be zero, that probability is given by the condition that all other bits that are taking part in the parity check constrain other than c_i bit they should have even parity.

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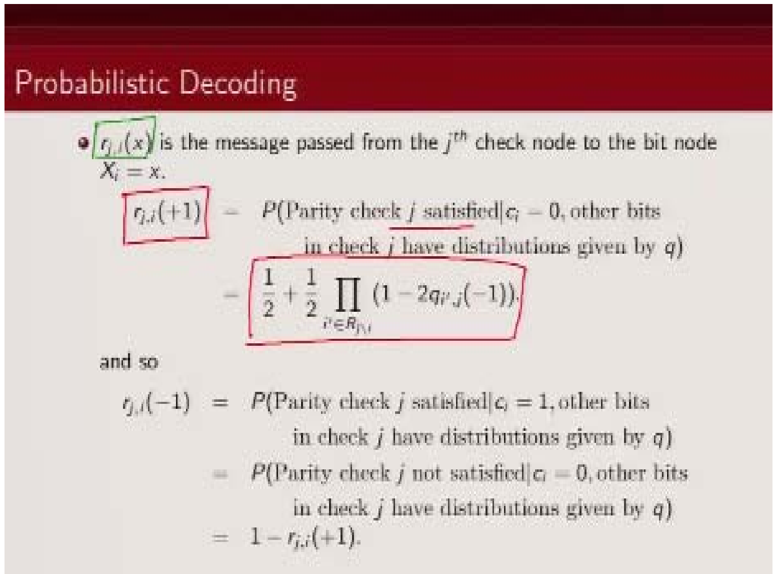

And that is given by this expression, similarly we can find out what is the probability that r $_{j,i}$ is -1 this is 1 minus this probability.

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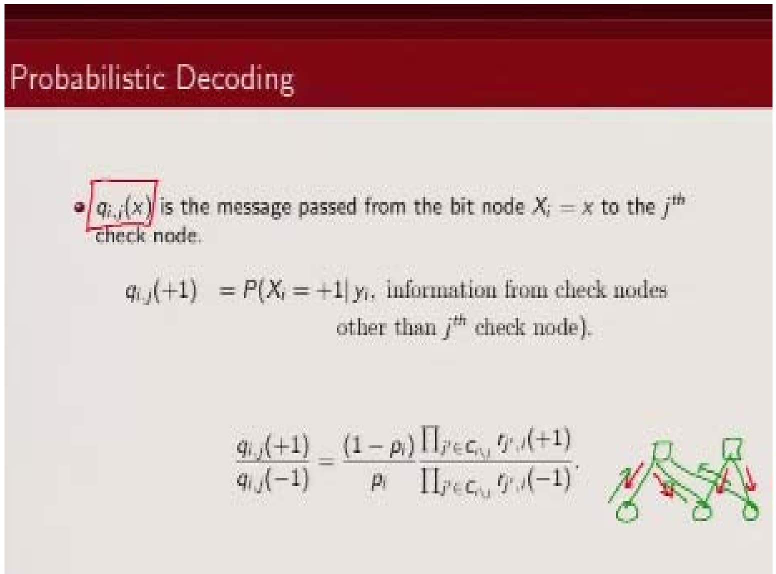

Now what is this $q_{i,j}$? It is a message passed from the bit notation i to the j^{th} parity check node.

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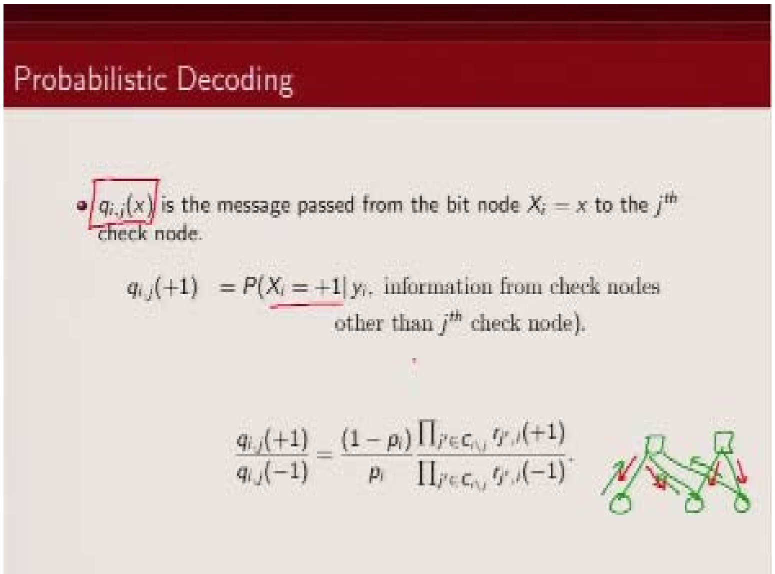

And this is so $q_{i,j}$ here being +1 is given by what is the probability that x_i is +1 given receive sequence y_i and information from parity check nodes other than the j^{th} parity check node so, what is happening is when you are decoding because each bits are participating in multiple parity check equations, so you are getting some independent information from other parity check nodes and that information you want to pass it to and spread it around in this network.

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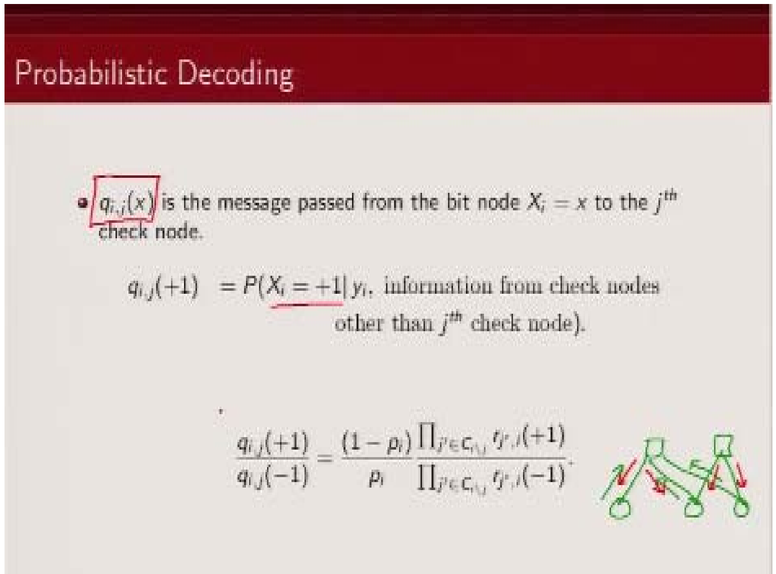

And this probability is given by this expression.

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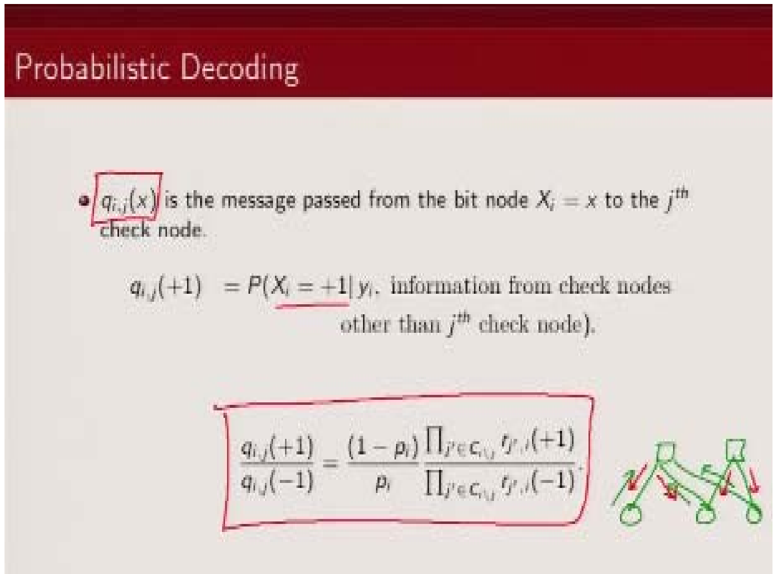

So there are two types of messages again I repeat which are being propagated in this graph, one is a message from the message nodes to the check nodes and then check nodes are sending some information saying okay whether these parity check constrain is satisfied or not, given input bit is one or zero and they are passing that information, so these information q_i's are passed from message nodes to the check node and this message, these messages r_i's have been passed from check nodes to the message node.

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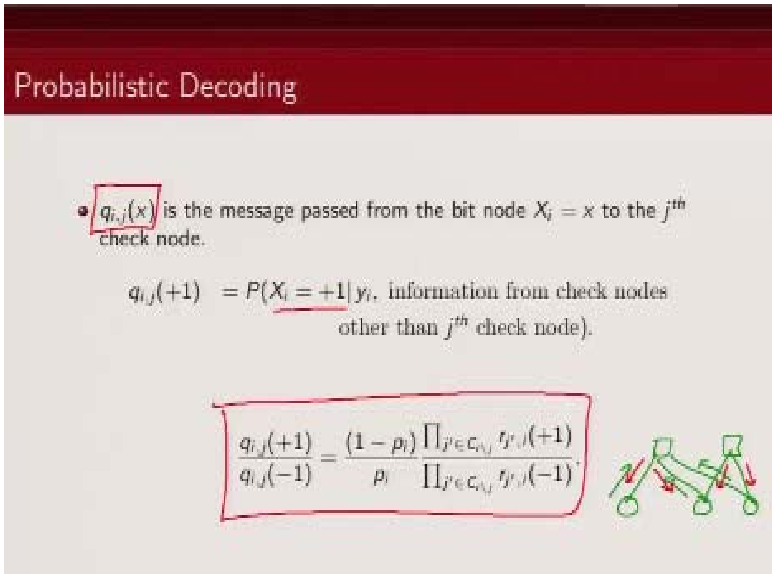

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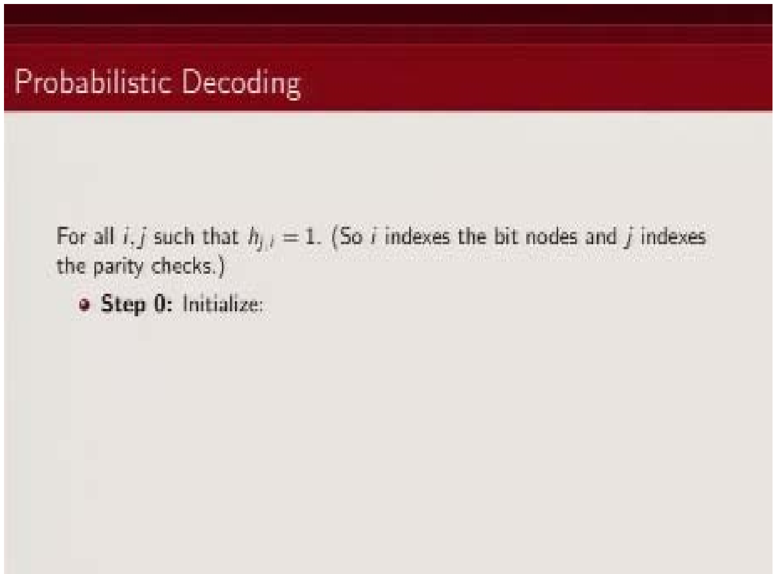

So then how does this whole process go? So first step is

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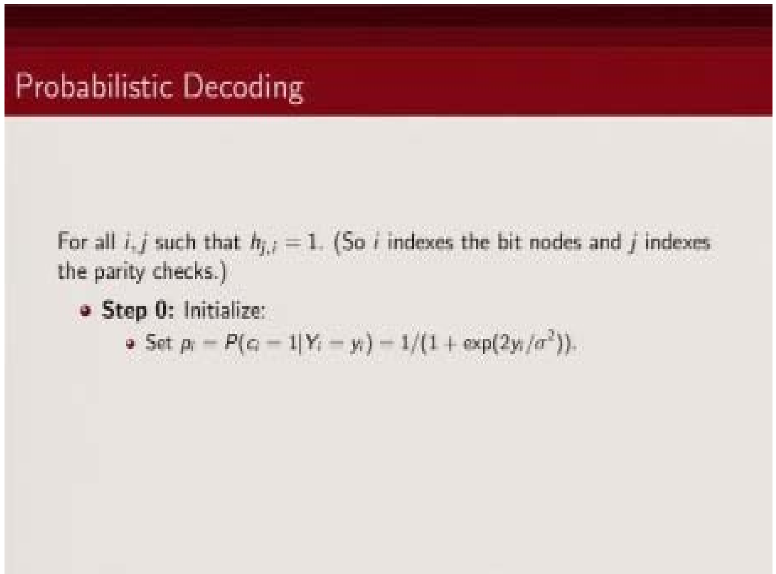

We initialize the probabilities that we are going to send from the message nodes to the check node.

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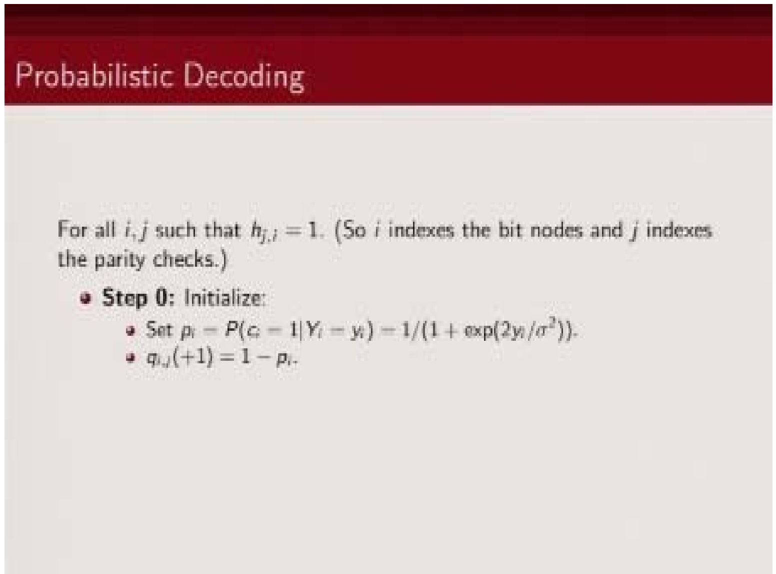

So we calculate this p_i.

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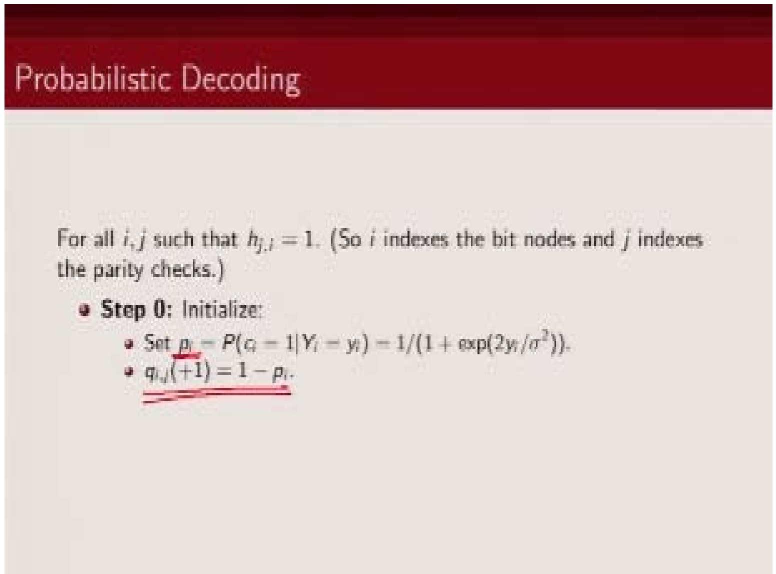

And we calculate this q_i's, these are messages we will send from the bit node to the parity check node okay.

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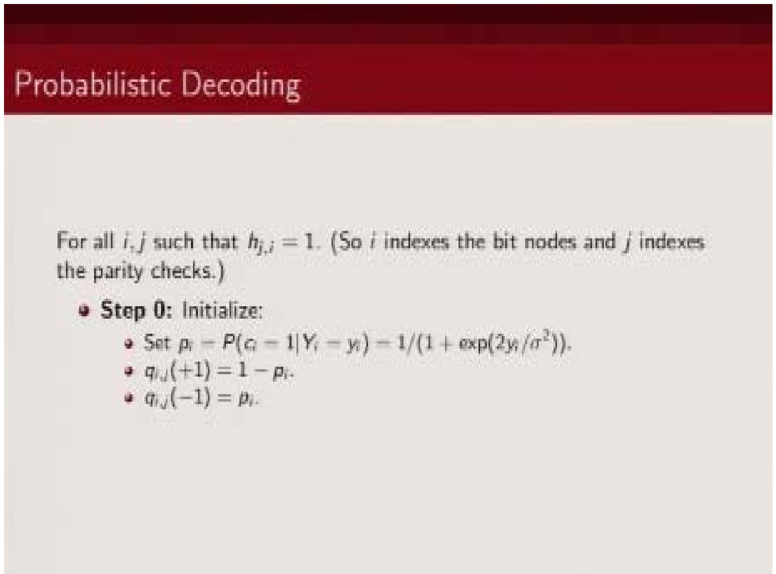

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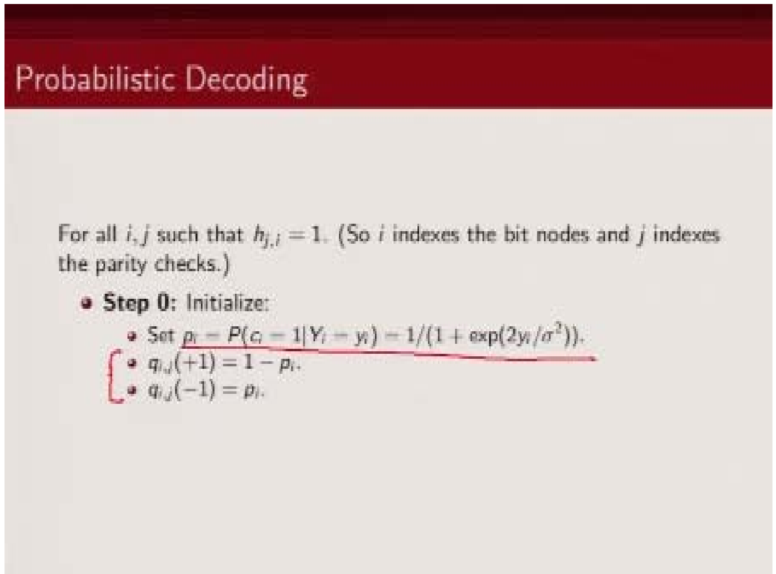

So that is the first step initialization step that we are calculating the initial messages that the bit nodes will send to the check node and that is basically based on channel likelihood values, it is given by this expression.

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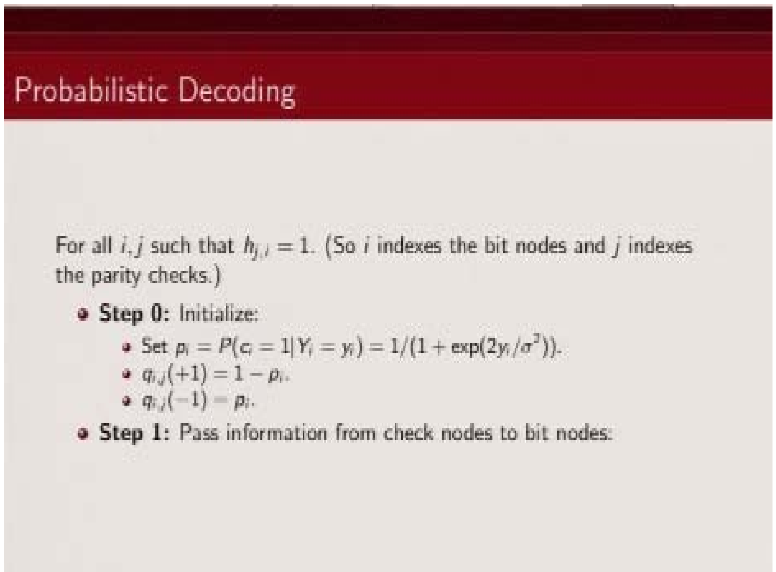

Next is once these messages are sent to check nodes then check nodes will do local computation and it will send this r_i's back to the bit node.

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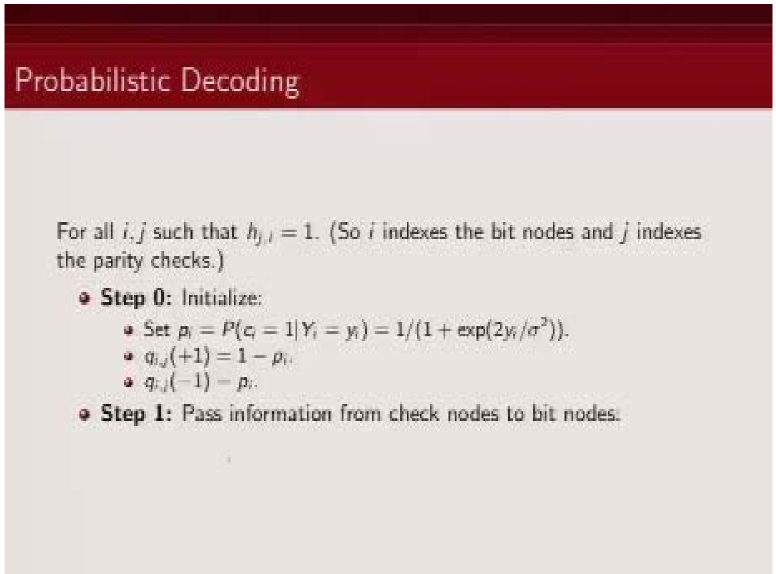

So pass information from check nodes to the bit nodes so check nodes are going to pass these information r_i's

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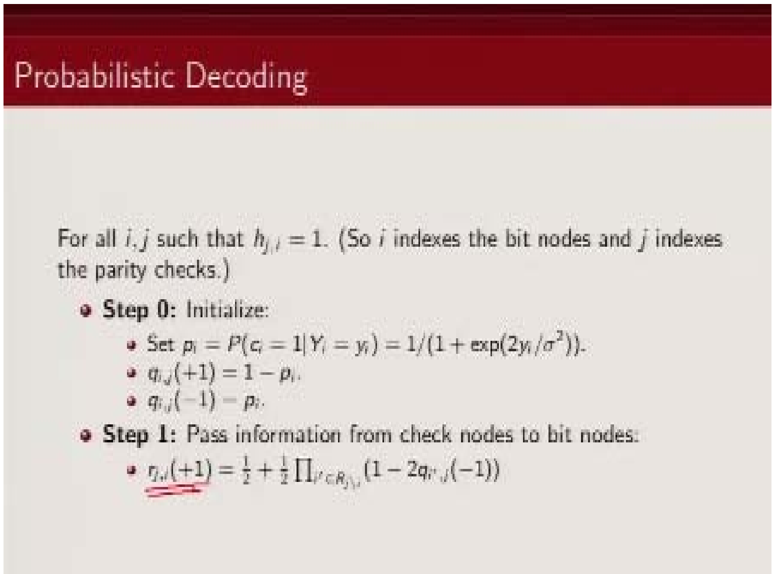

Back to the bit nodes.

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Probabilistic Decoding

For all i, j such that $h_{j,i} = 1$. (So i indexes the bit nodes and j indexes the parity checks.)

- **Step 0:** Initialize:
  - Set $p_i = P(c_i = 1 | Y_i = y_i) = 1/(1 + \exp(2y_i/\sigma^2))$.
  - $q_{i,j}(+1) = 1 - p_i$.
  - $q_{i,j}(-1) = p_i$.
- **Step 1:** Pass information from check nodes to bit nodes:
  - $r_{j,i}(+1) = \frac{1}{2} + \frac{1}{2}\prod_{i' \in R_{j \setminus i}}(1 - 2q_{i',j}(-1))$
  - $r_{j,i}(-1) = 1 - r_{j,i}(+1)$.

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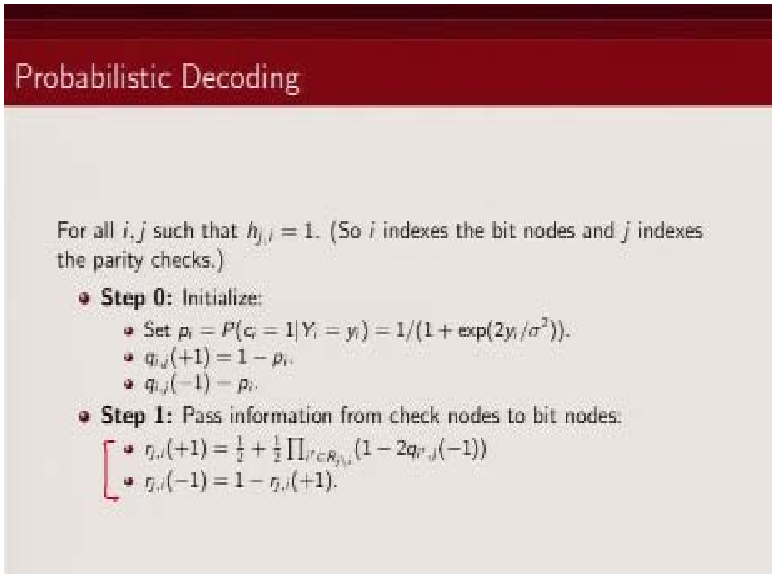

And this is given by this expression.

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Now once you get this updated r_i's from various check nodes then this q_i's are updated.

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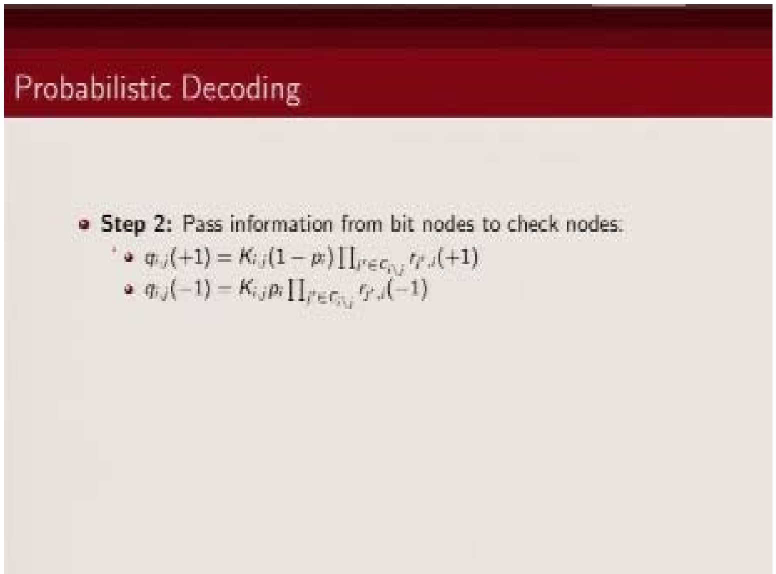

So you are going to then send modified information, this $q_{i's}$ to the parity check nodes.

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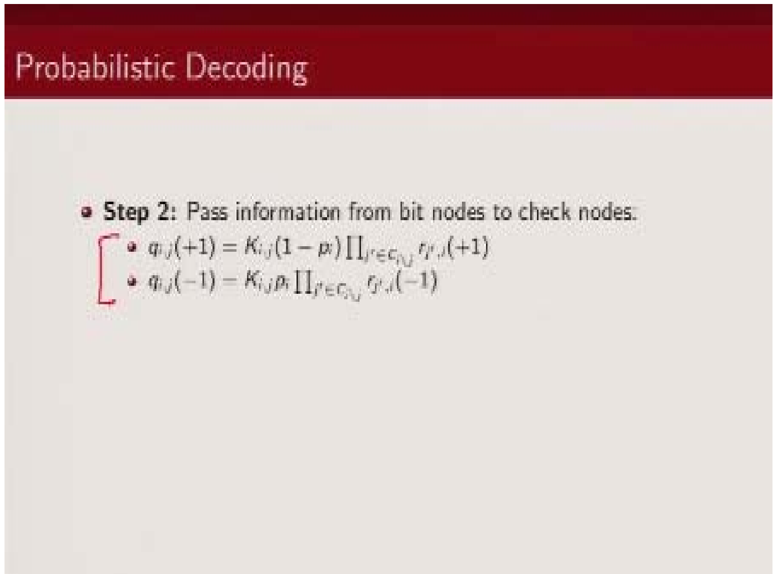

And this is basically given by this.

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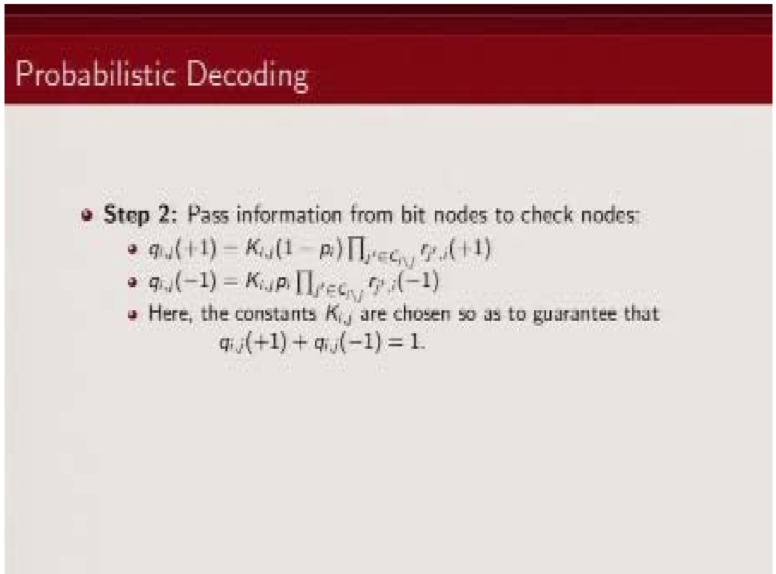

You can do some normalization, these are k_i's are just some constant, you can do some normalization.

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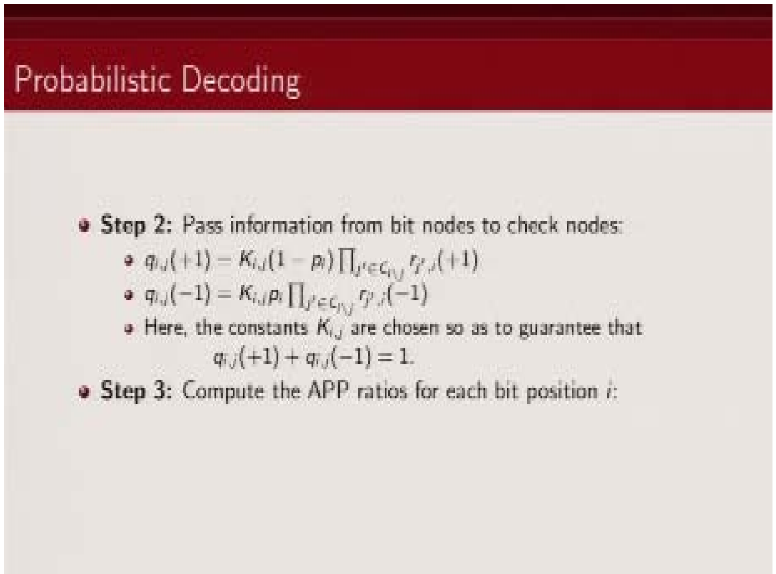

And finally we will compute the A pository probability.

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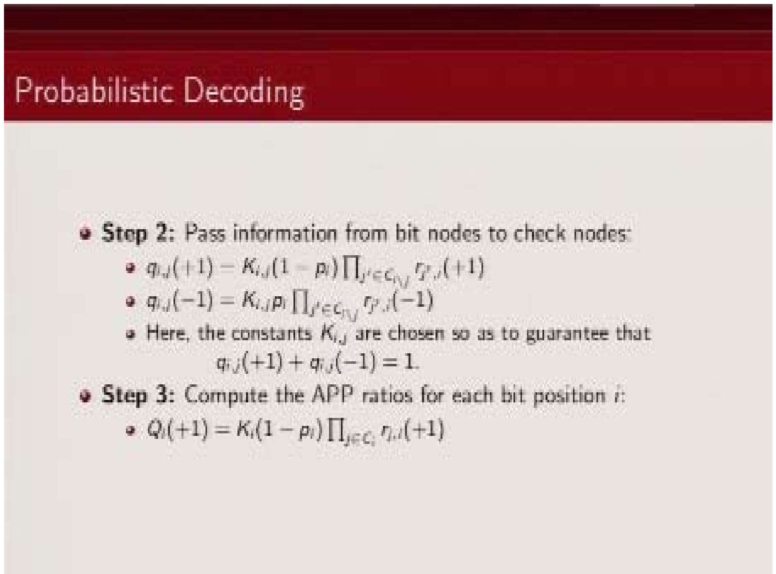

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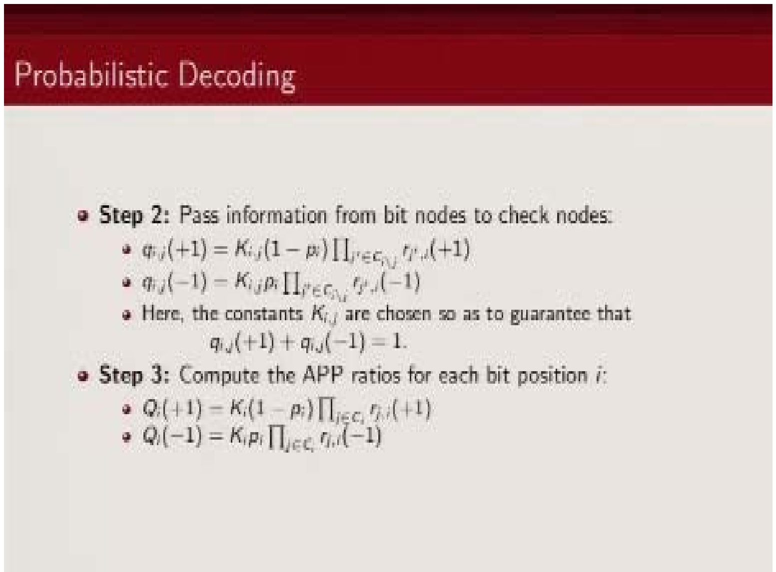

And that is given by this expression.

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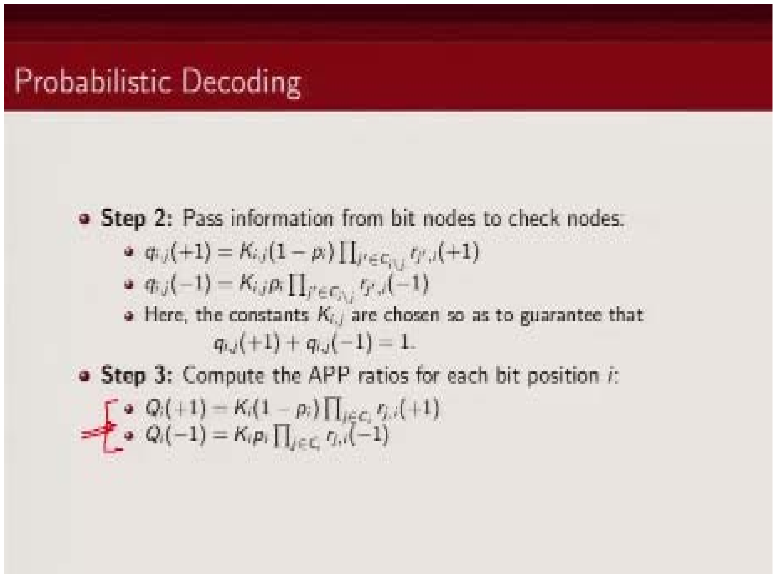

And this we have derived earlier in the lecture okay. So to repeat basically how this whole process is going, you have this received values from the channel, based on that you compute your initial p_i's and q_i's, now this information are sent to a check nodes, now check nodes do local computation that what is the probability that the check node will be satisfied given a particular bit c_i is zero or one and then they pass that information to along the edges back to the bit nodes.

Now these bit nodes are getting information from other check nodes as well because each bit node is connected to multiple parity check equations. So it takes those input into a count to updates its q_i's and this process is continued in an iterative fashion until all the parity check constraints are satisfied.

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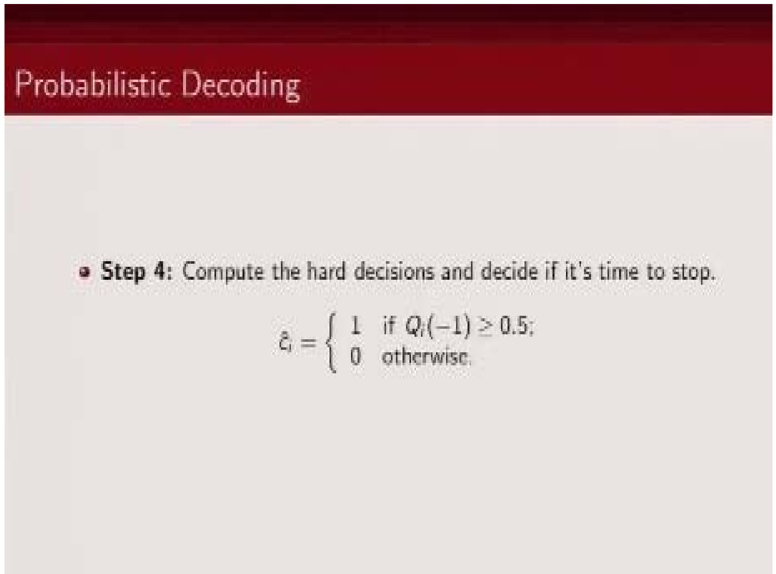

So finally basically once you compute the a pository probability then if q_i being -1 is more than 1 you decide in favor of 1 otherwise you decide in favor of zero.

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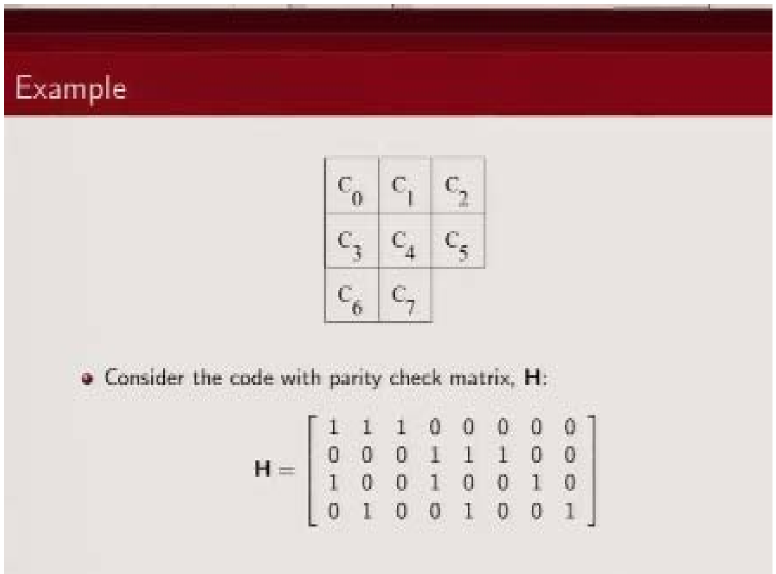

So let us take an example to illustrate the decoding algorithm, so we have a low density parity check matrix given by this we have eight coded bits.

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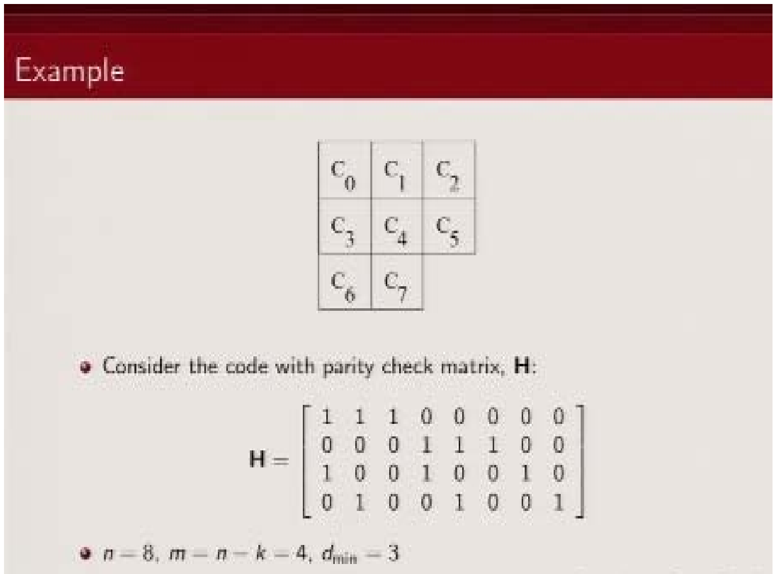

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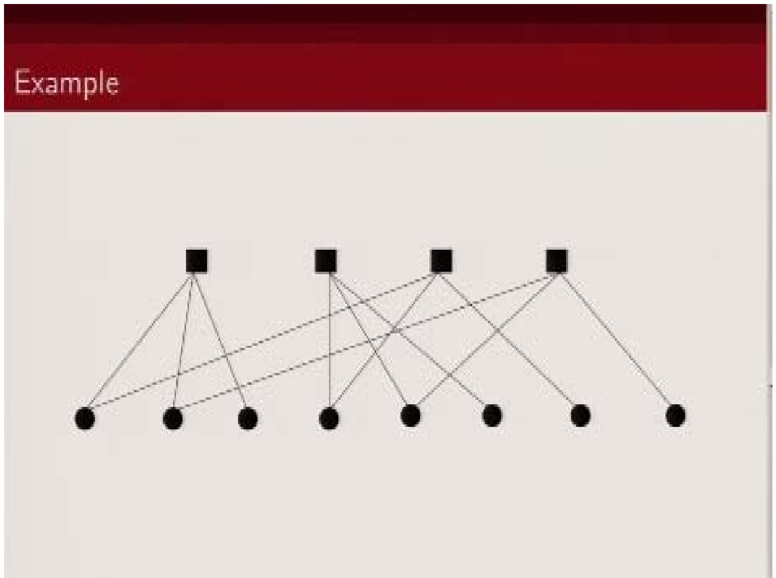

This is the tanner graph corresponding to the parity check matrix, we can just quickly check it.

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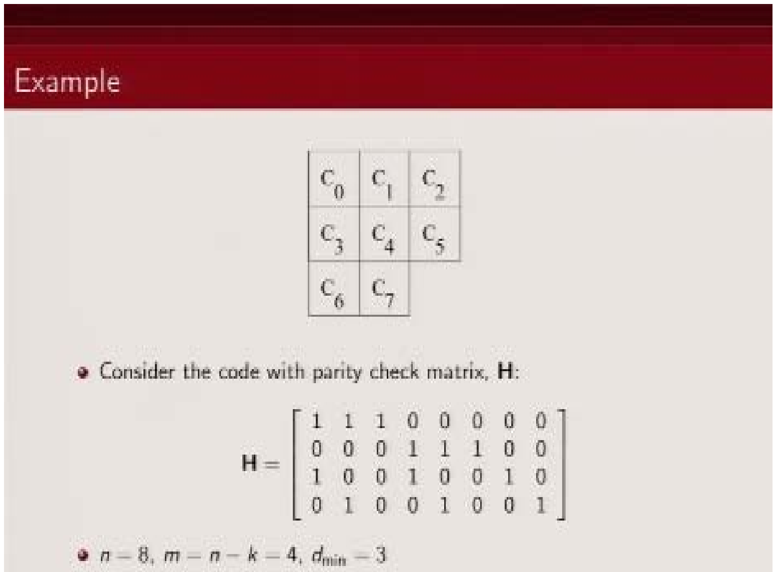

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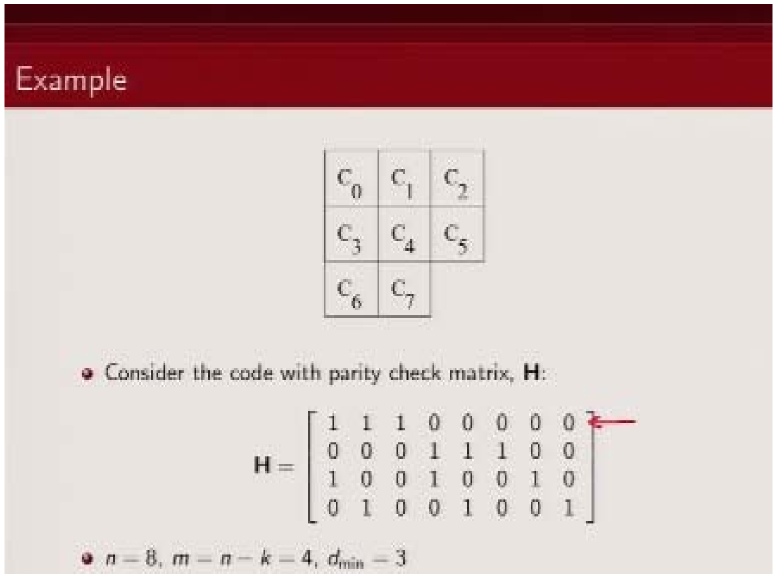

So the first parity check equation involves these three bits first three bits.

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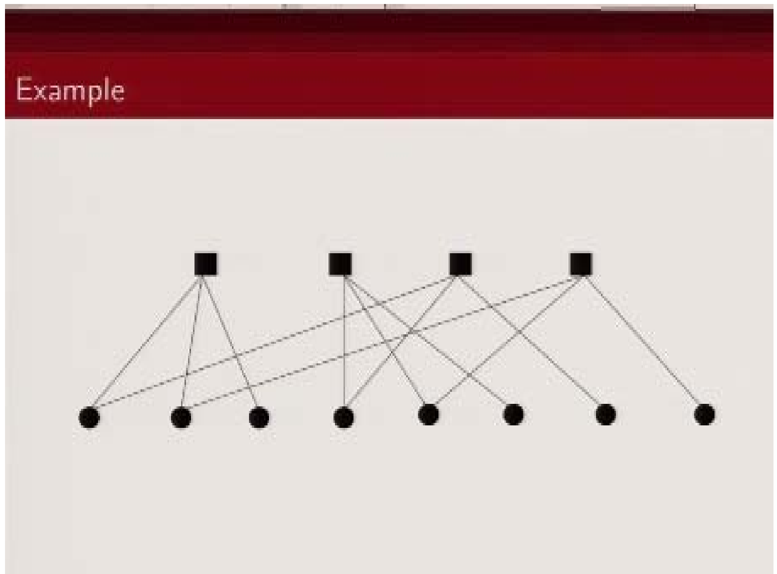

So you can see the first parity check equation involves this, this, and this.

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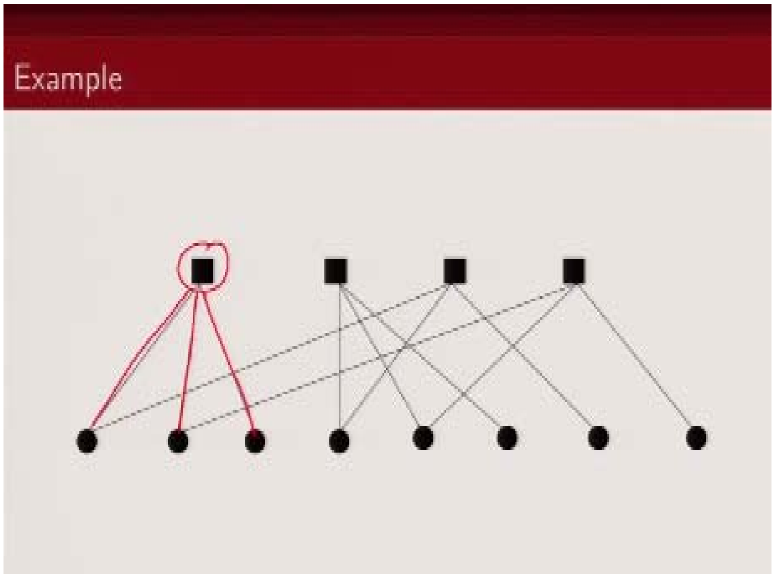

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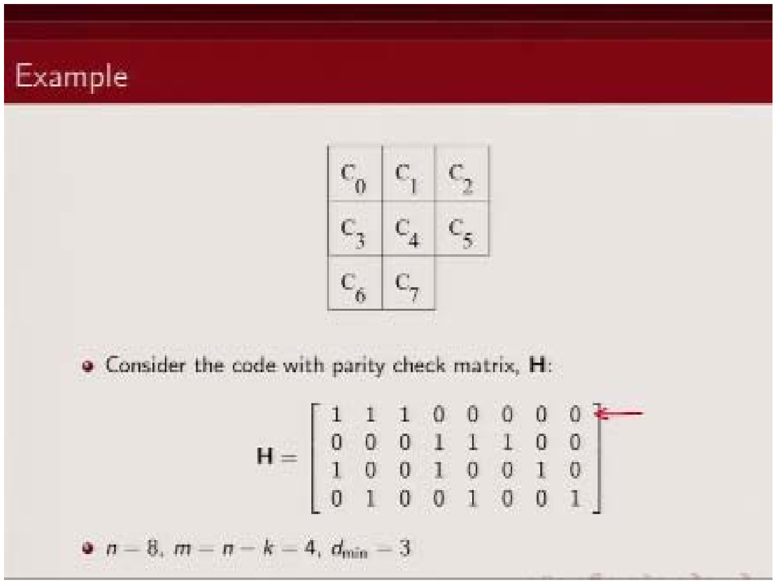

Second parity check involves fourth, fifth, and sixth bit.

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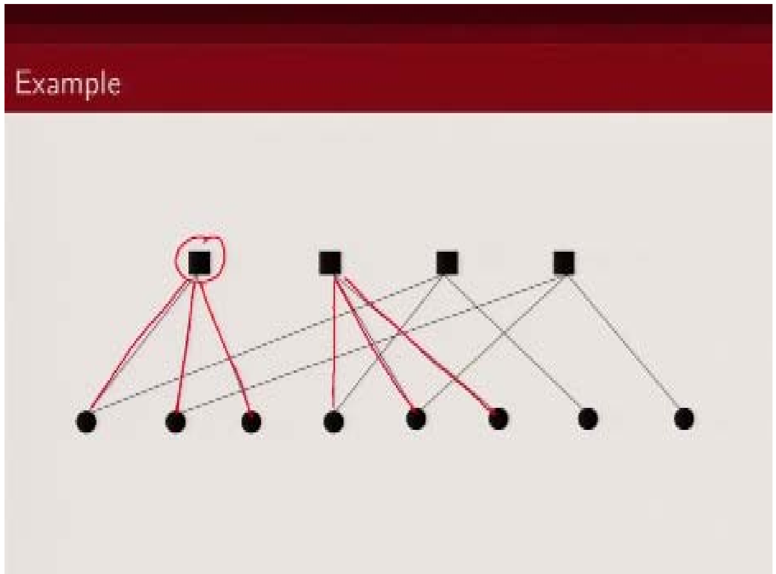

That is second parity check involves fourth, fifth, and sixth bit.

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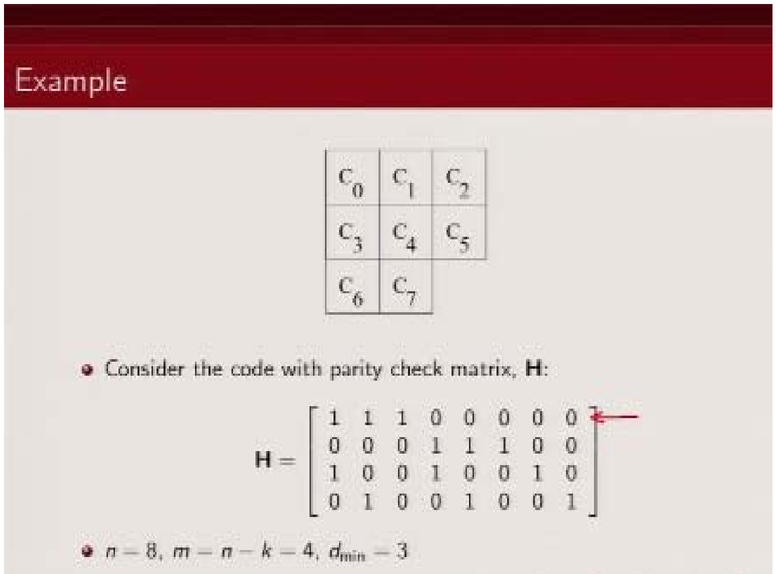

This involves first, fourth, seventh.

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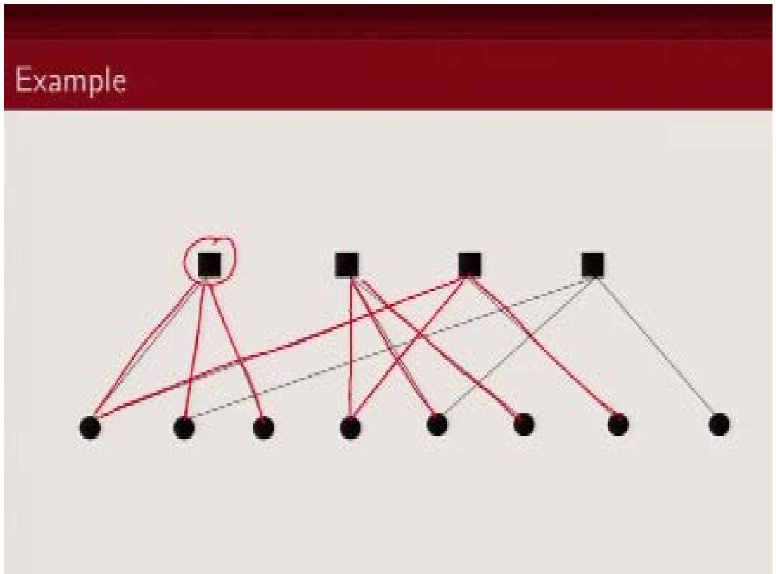

And that is first, fourth, and seventh, and similarly we can verify for this also okay, so this is a tanner graph corresponding to the parity check matrix that we have drawn.

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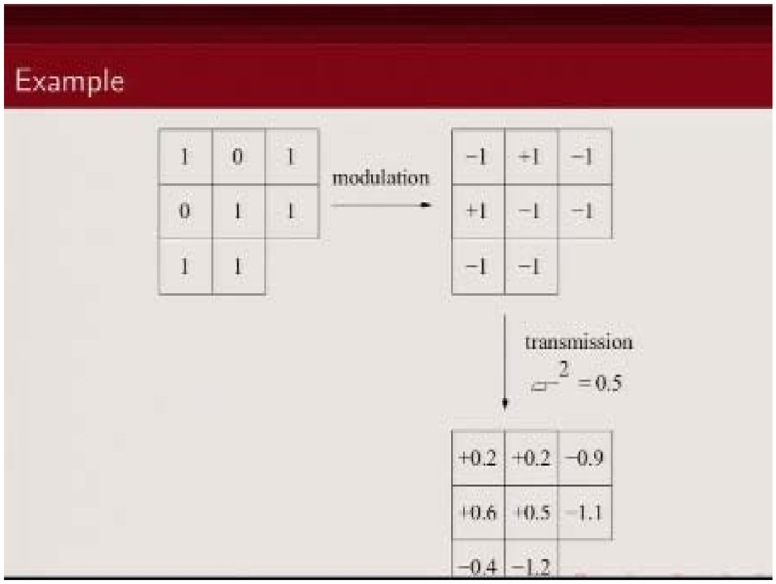

So these are the bits, eight bits which were transmitted now after modulation because we were mapping them as $(-1)^{c_i}$.

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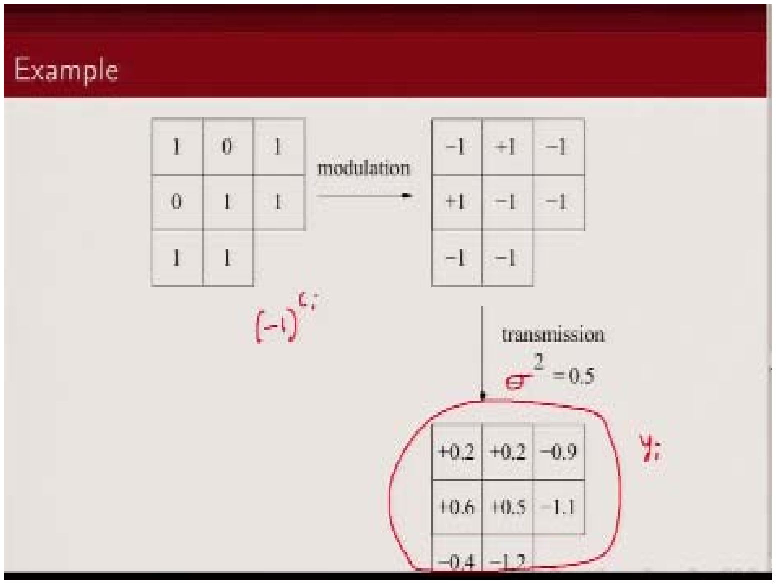

So one is getting mapped to -1 and zero is getting mapped to +1, so that is, these are the modulated bits and noise variance was 0.5 so what we get is these are the received value so these are my y_i's okay. Now what is the first step? I will take this y_i and I will compute my p_i's and q_i's

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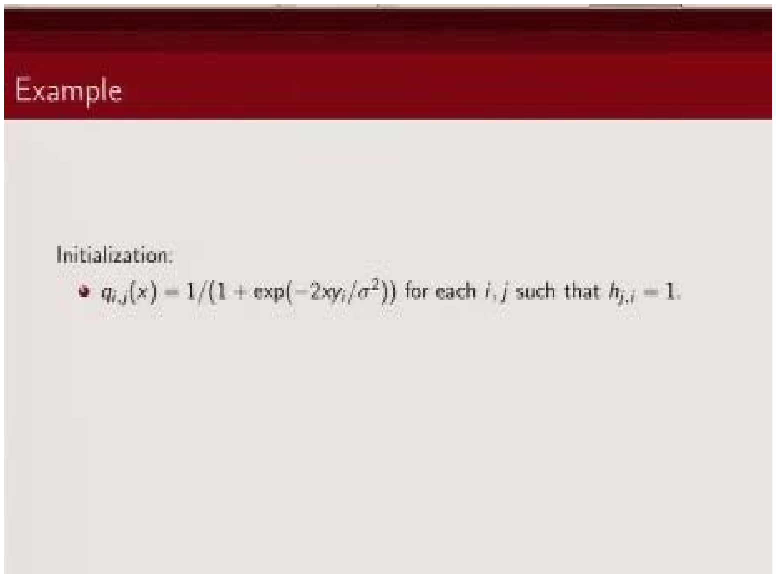

Initial p_i so I am going to first compute my initial q_i's

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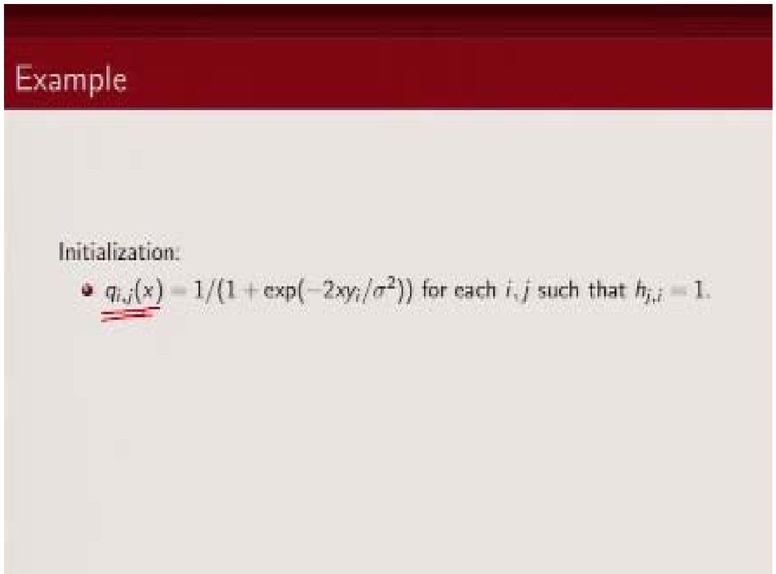

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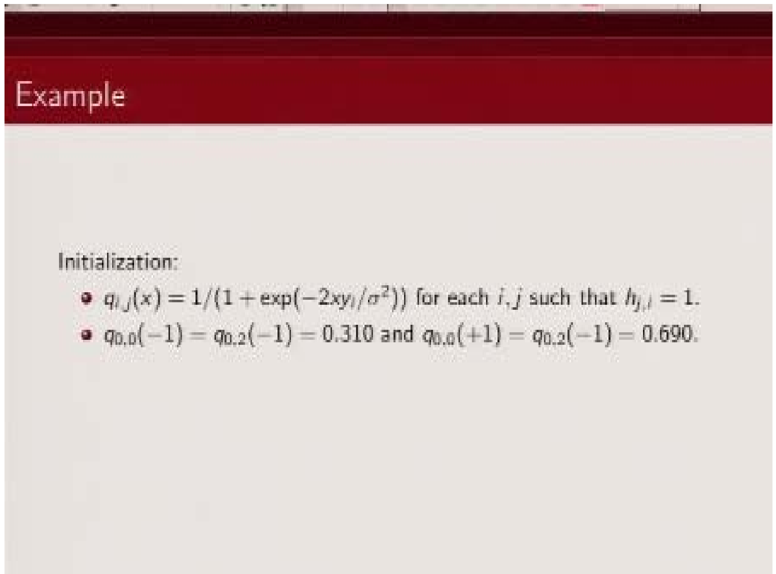

And that is basically given by this expression.

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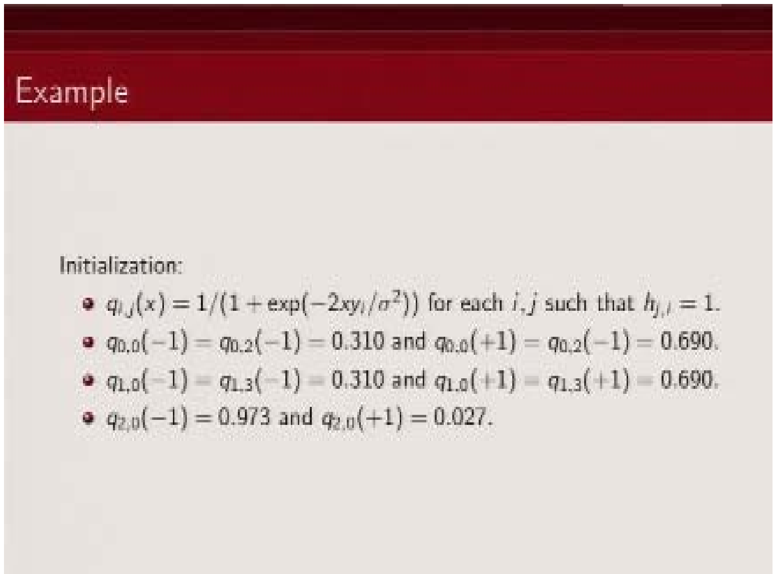

So I am just stating this, so I compute this q_i's, now again just pay little attention to what q_i's are.

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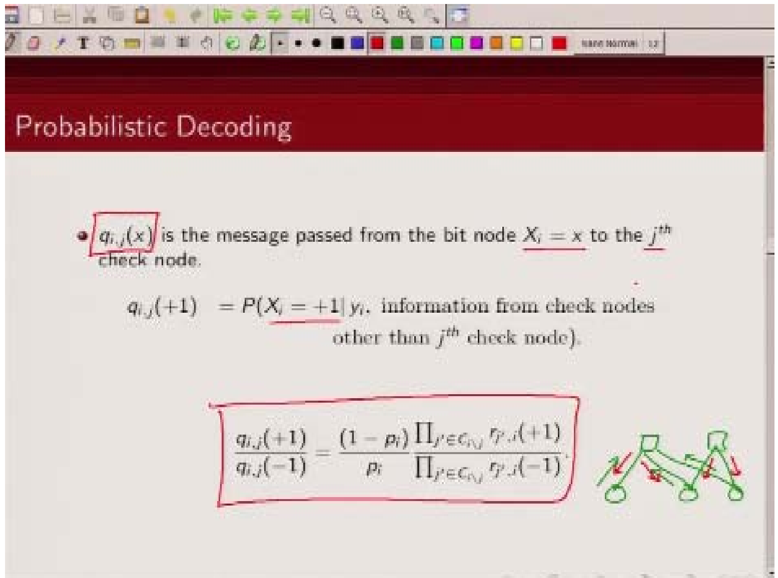

q_i's are message passed from i[th] bit to the j[th] parity check constraint. So if you label your nodes from 0,1,2,3,4 as similarly label parity check constraints, so what you are going to notice is so you need to compute your q_i's for, for in this example.

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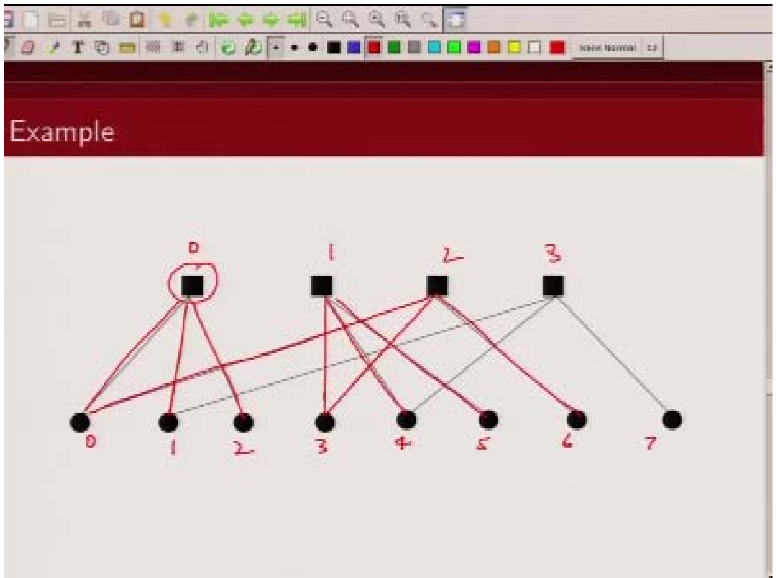

So this is 0, 1, 2, 3, 4, 5, 6, 7, similarly it is a 0, 1, 2, 3, so you will compute $q_{0,0}$.

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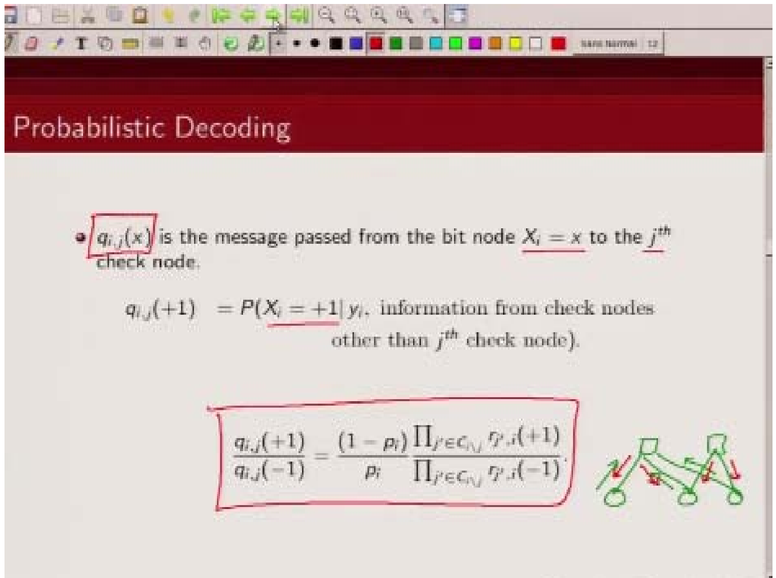

So $q_{i,j}$ is the message passed from i^{th} node to the j^{th} check node right. So q_{ij}'s you need to compute for in this particular example.

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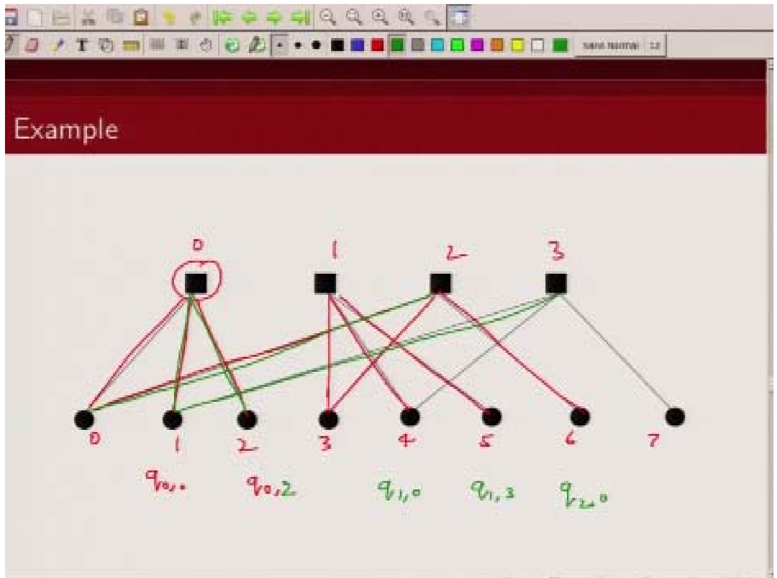
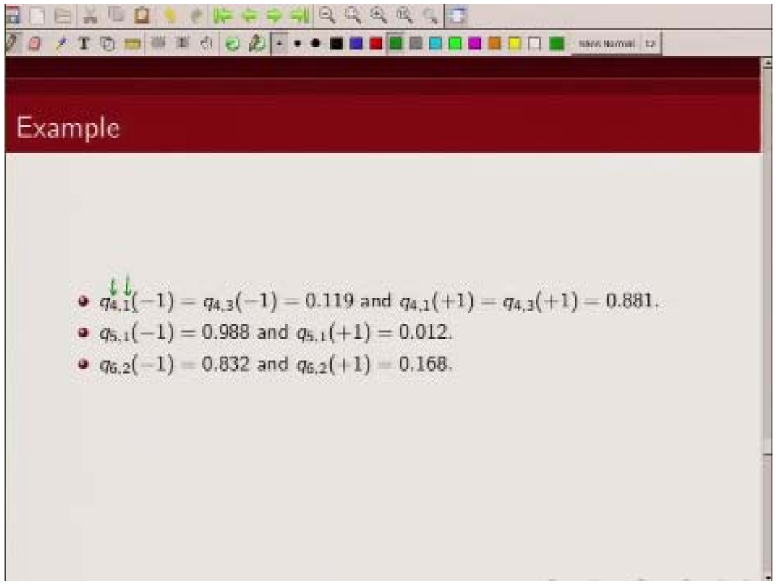


So let us look at 0[th] node, so you need to compute q_{00} because your message you are sending from 0[th] node to 0[th] parity check. You need to compute q_{02} because you are sending message from 0[th] bit to the second this thing. You need to compute this q_{10}, you need to compute q_{13} right. You need to compute q_{20} and how are these initially computed, these are initially computed based on what are the received values y_i's that we have received. And that is precisely what I have shown here.

(Refer Slide Time: 35:02)



So I have, you can see here these are the computed values of q_i's and pay close attention to these instances, these denote that i^{th} bit is sending information to the j^{th} parity check constraint okay.

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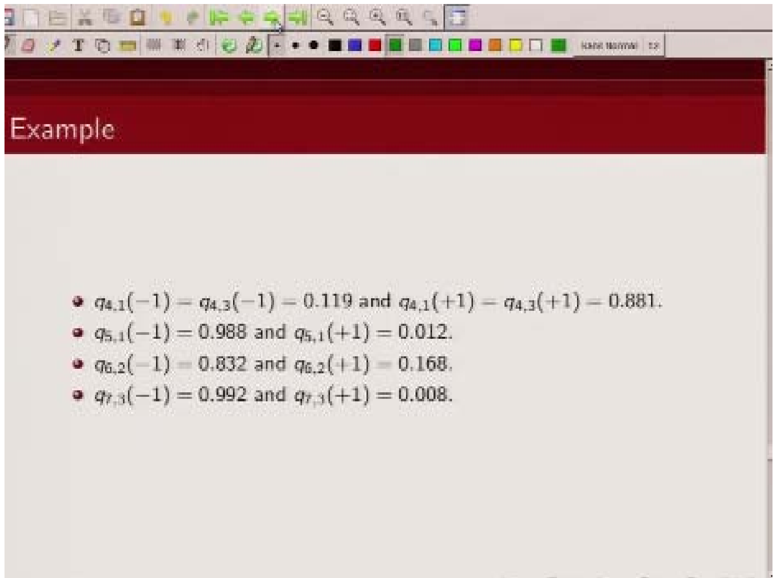

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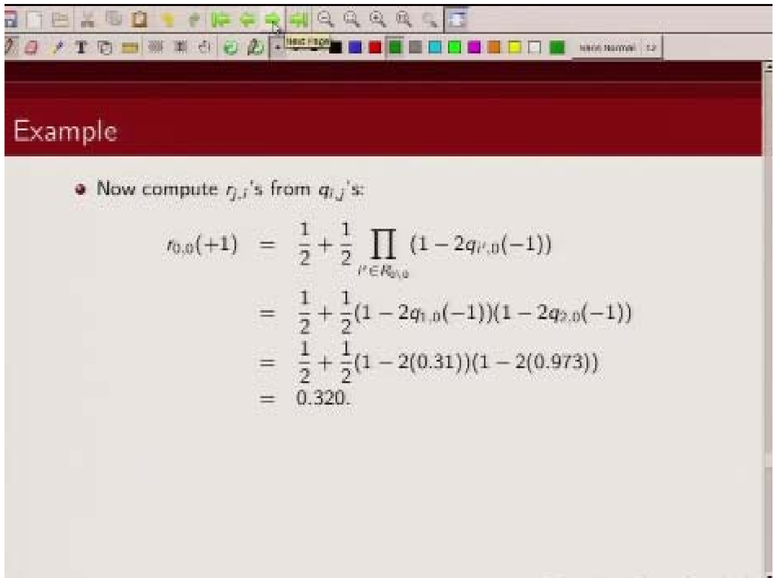

So once we have computed this q_{ij} the next thing that we need to do is these parity check constraints are now going to check okay given that the bit is zero. What is the probability that parity checks constraint is satisfied, given the bit is one what is the probability that parity check constrain is satisfied?

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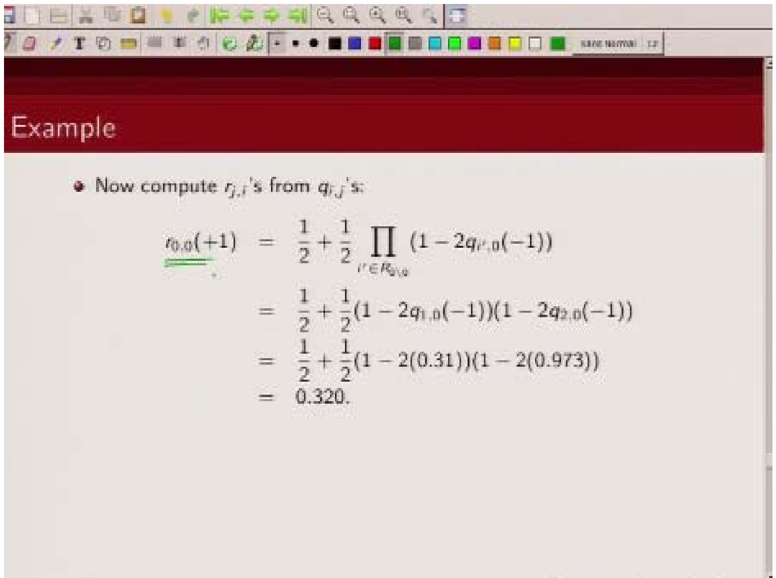

And those are given by these r's, $r_{i,j}$'s right. What is the probability that 0^{th} parity check constraint is satisfied given the 0^{th} bit is +1. Now what is that probability, that probability is given by, so we are looking at first parity check constraint. Now given that first bits C_i is zero what we want is the other bits which are involved in the parity check constraints they should have even parity. So let us look at the H matrix for the first row.

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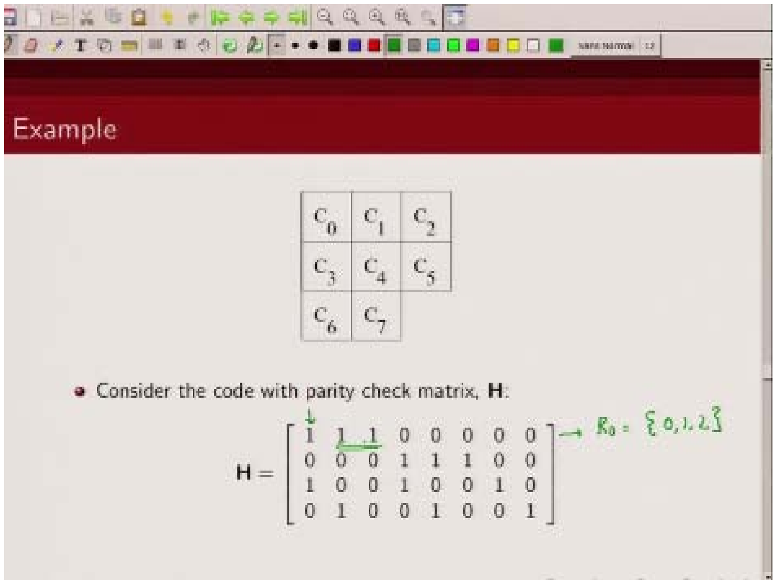

So this is R_0, R_0 is 0, 1, and 2. So given that this bit is zero what we want to find out it is what is the probability that sum of these two add up to even parity. And that is what we are doing here.

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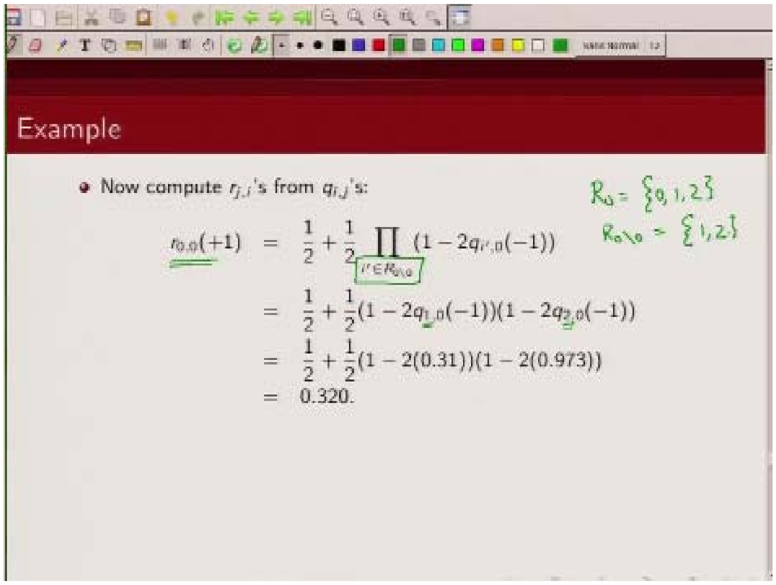

Note here, i^{th} belongs to R_0 minus this zero term. So here you will have two terms, one is corresponding to i being one and other i being two. Why because your R_0 was 0, 1, 2, so R_0 minus this element zero is nothing but 1 and 2. So here in this product you will have two terms, one corresponding to $q_{1,0}$ other corresponding to $q_{2,0}$. Because in that 0^{th} parity check equation other than the first bit, the bits that are participating is that other than

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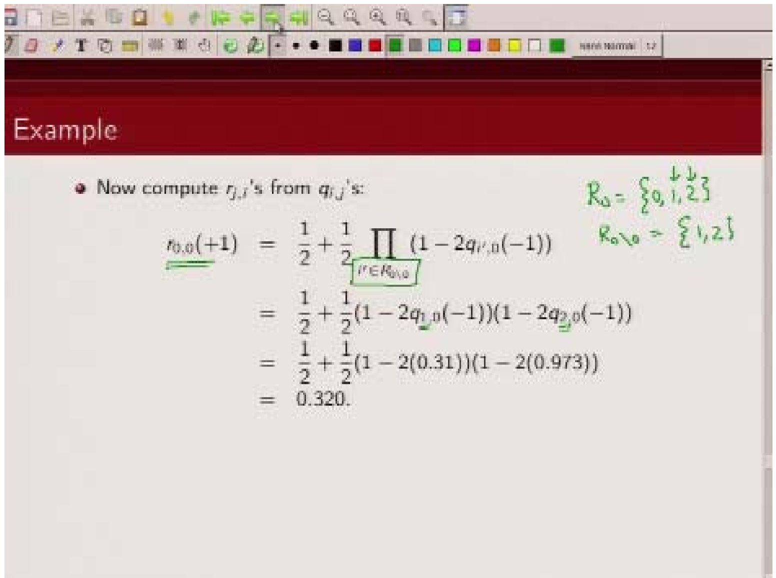

The 0^{th} bit other bits which are participating is bit number one and bit number two. So this is the probability that parity check constraint is satisfied given C_i is zero.

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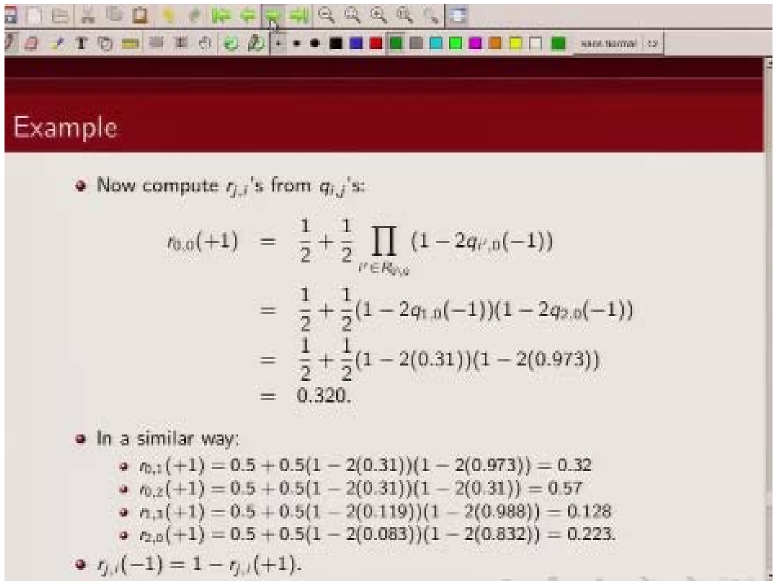

And similarly we can calculate the other r_i's. I am not going into detail of that it is just the same procedure repeated. So once we calculate this q_i's, r_i's and initial q_i's.

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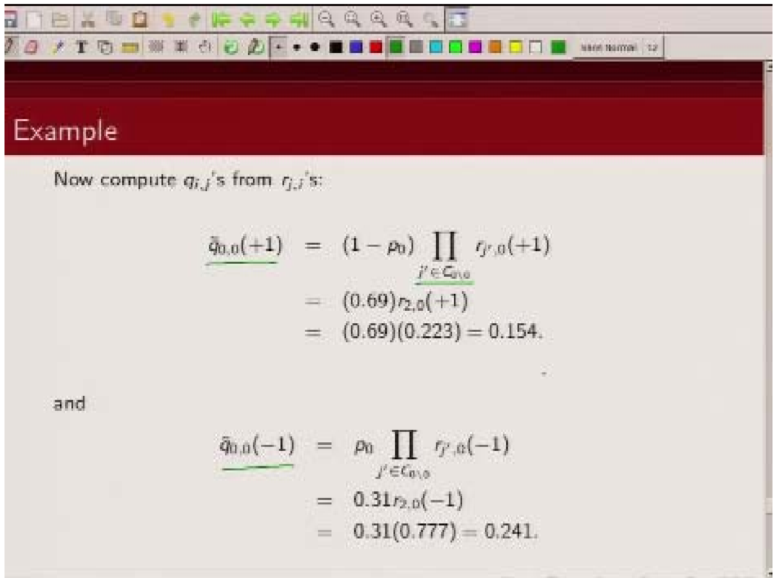

Then we are going to update our q_i's. And again we follow, so we find the product over all those check equations other than that particular bit and we repeat this for $q_{i,j}$ being +1 and -1. And we can normalize these probabilities so that they sum up to.

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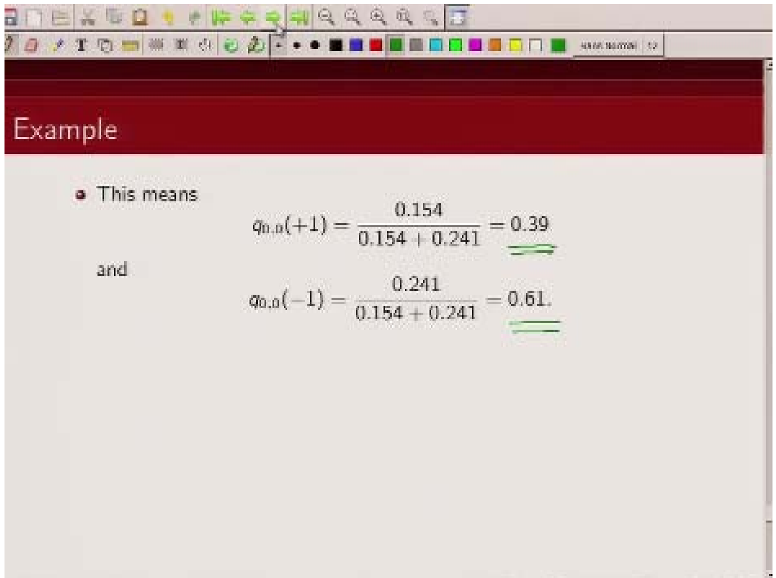

One, so if we normalize it these are the probabilities that we are getting right.

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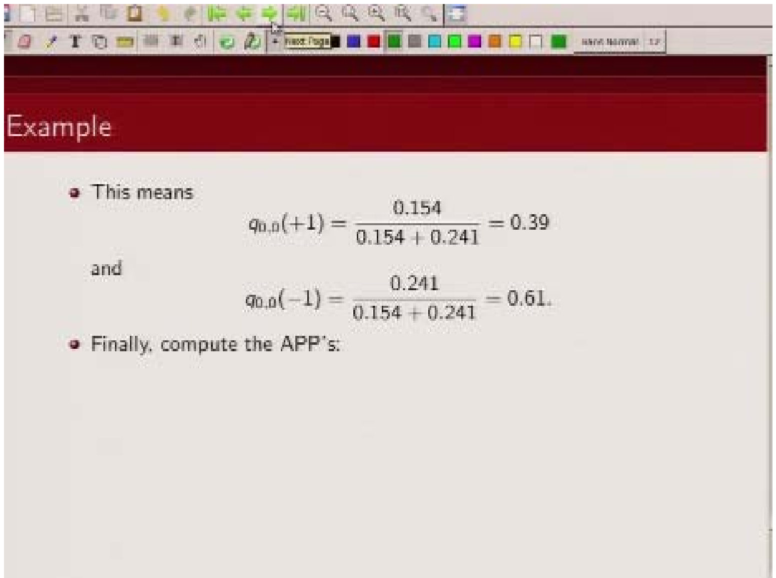

And next thing finally after we have computed one round of iteration, what is one round of iteration, you send these q_i's to a check node then check node gives you backs r_i's you update your q_i's.

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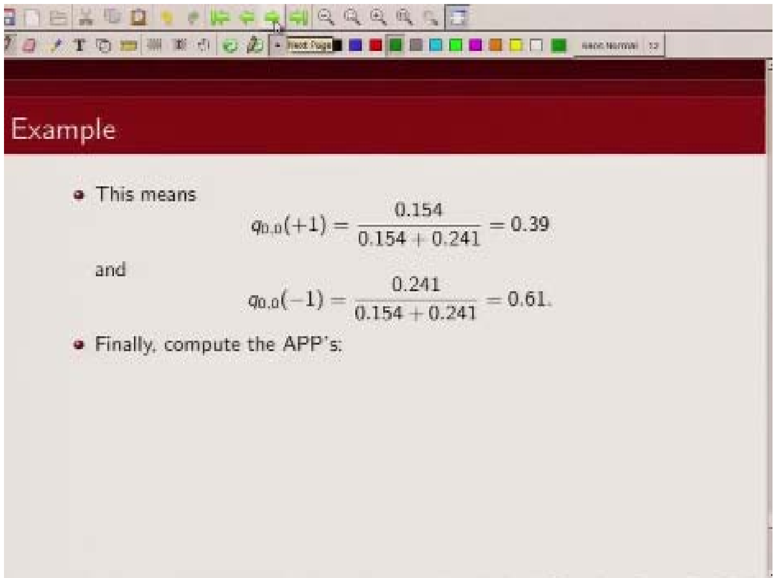

And once you do that.

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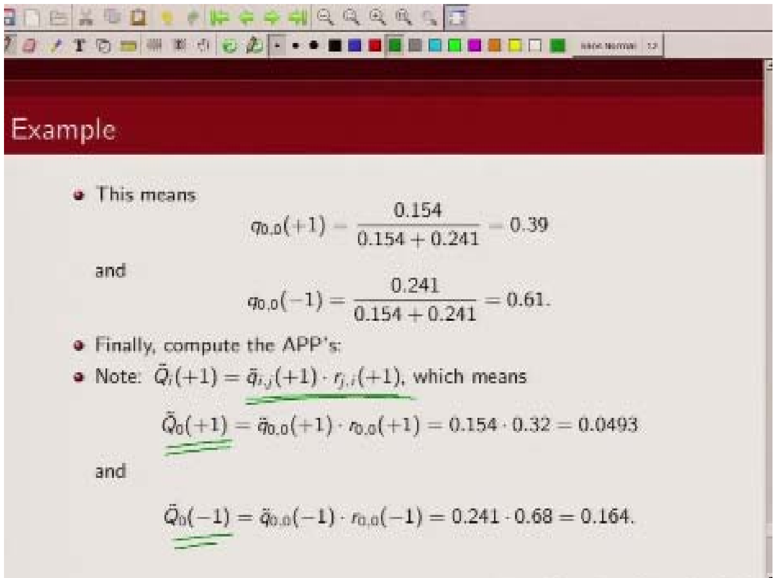

You can then find out the A posteriori probability which we have done here. So probability of wit being one, probability of this being zero, and then based on again you can normalize.

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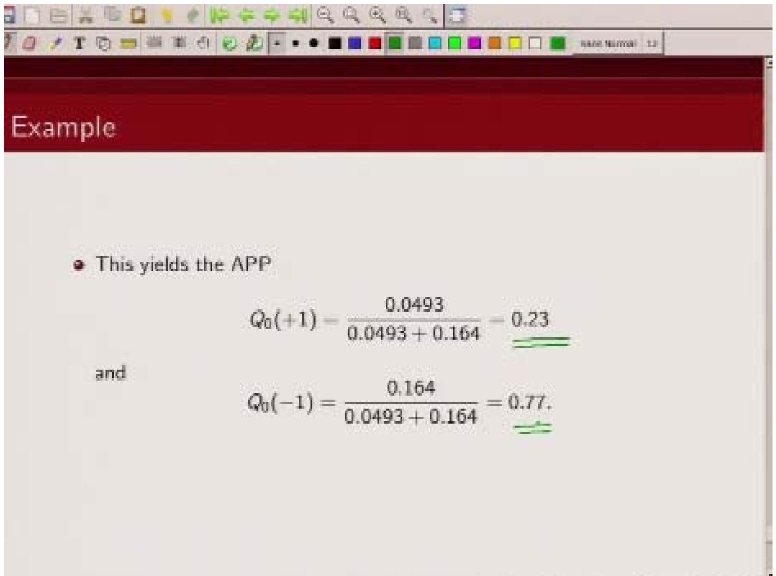

These probabilities so that comes out to be this. Now based on whichever is more likely you decide in favor of that. In this case q being -1 is more likely so a bit which was transmitted was one okay. So to recap how this probabilistic decoding algorithm works, you have your receive six sequence. You compute this probabilities q_i's message bits, send it to the check bits, check bits then do some compute local computation sends the information back. Now this process goes on and on until basically all the parity check constraints are satisfied.

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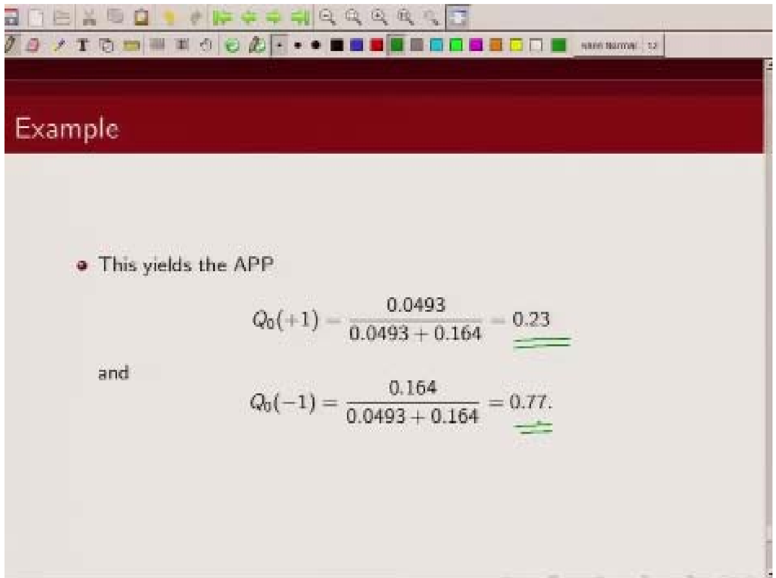

Or the maximum number iterations have reached.

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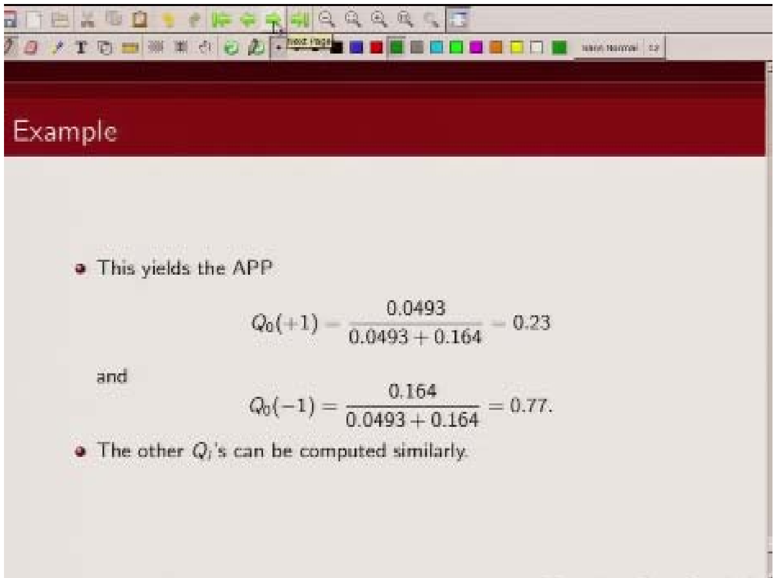

Now this we have done for the first bit you can do the same thing for other bits as well. In fact, the beauty of this algorithm is you can do this whole operation parallely.

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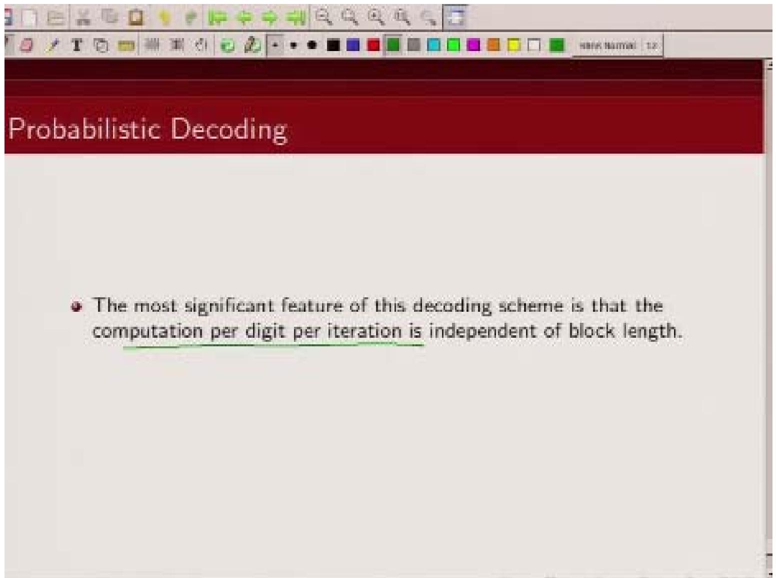

So one of the nicest feature of this is, this algorithm is computation per bit per digit is independent of block size.

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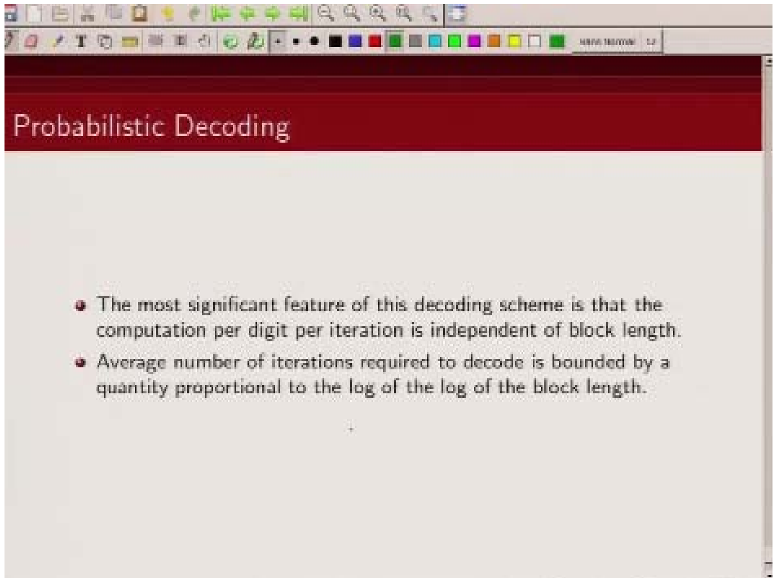

And average number of iterations required basically your decode is typically bounded by log, log of n. After that you started getting code related information back. So with this we will conclude our discussion on probabilistic decoding of LDPC codes. Thank you.

Acknowledgement

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