Data Mining and Machine Learning

Speech Recognition using HMMs – Viterbi Decoding

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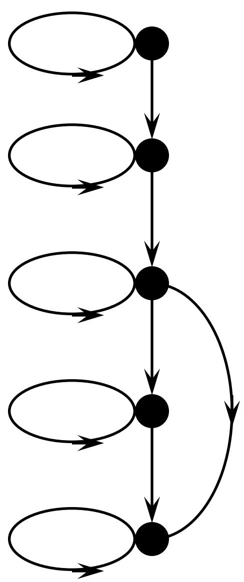
Viterbi Decoding

- Viterbi Decoding is the algorithm which is used to find the sequence of HMM states (or HMMs) which is most likely to have generated a given observation sequence
- Similar to the Forward Probability calculation

Viterbi Decoding (1)

y_1 y_2 y_3 y_4 y_5 y_{t-1} y_t y_T



Q: How can *M* have generated *Y*?

A: Via a state sequence of length T

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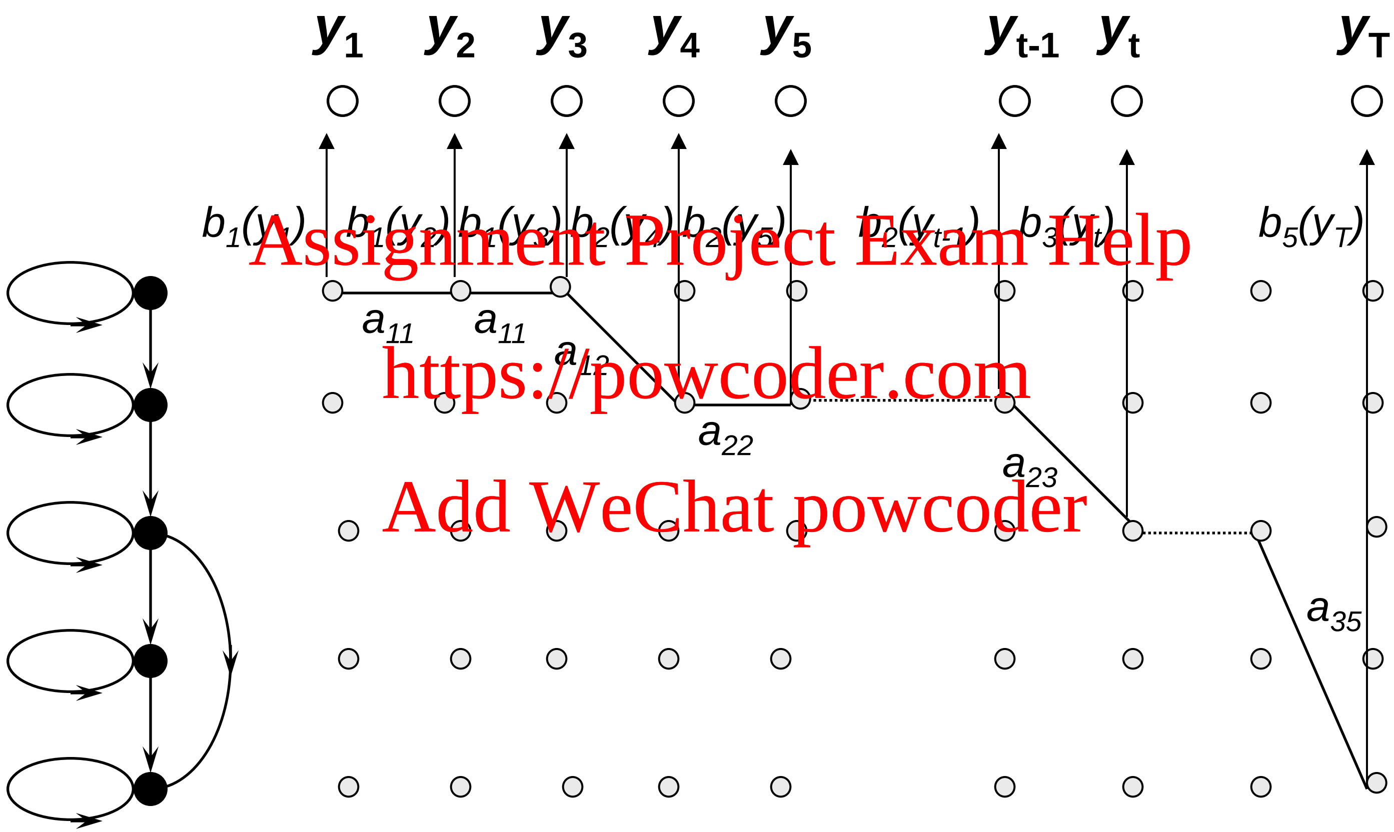
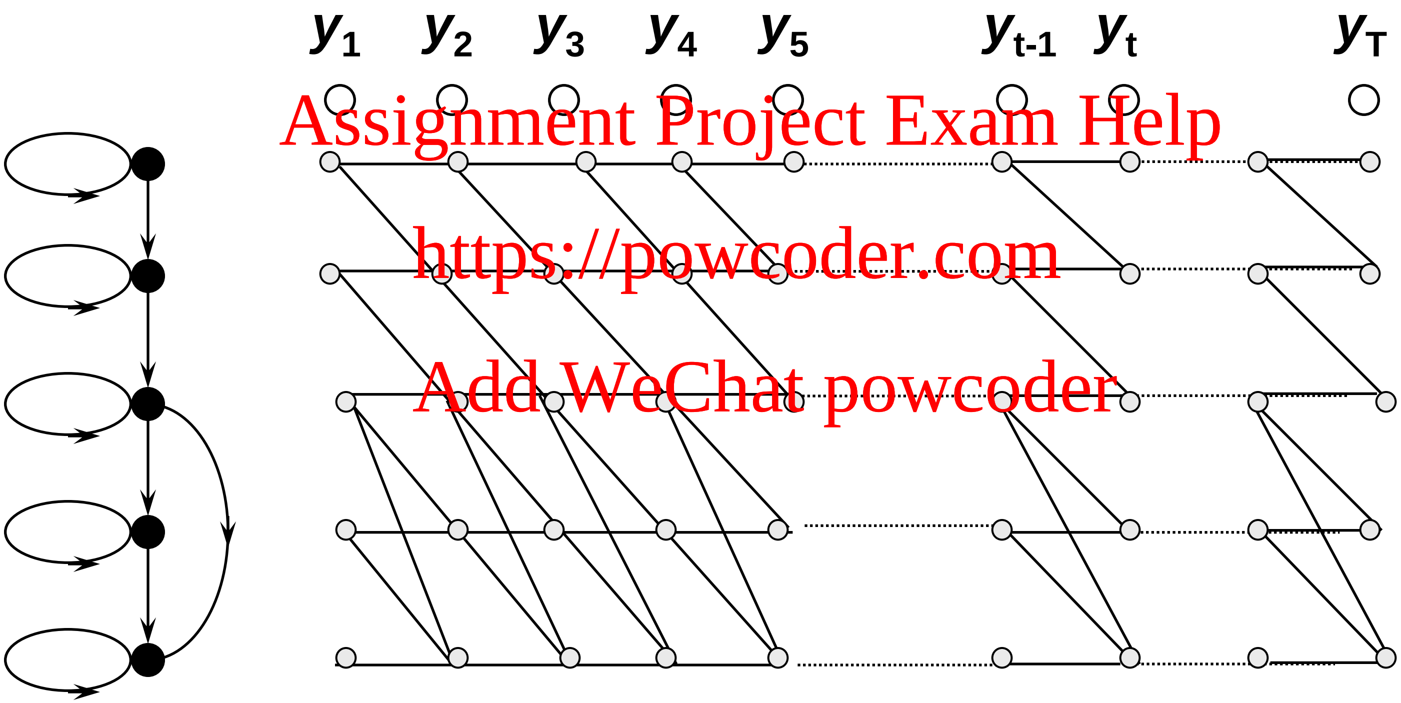
Basic Probability Calculation



Viterbi Decoding (2)

- **Construction of ‘state-time trellis’**



Viterbi Decoding (3)

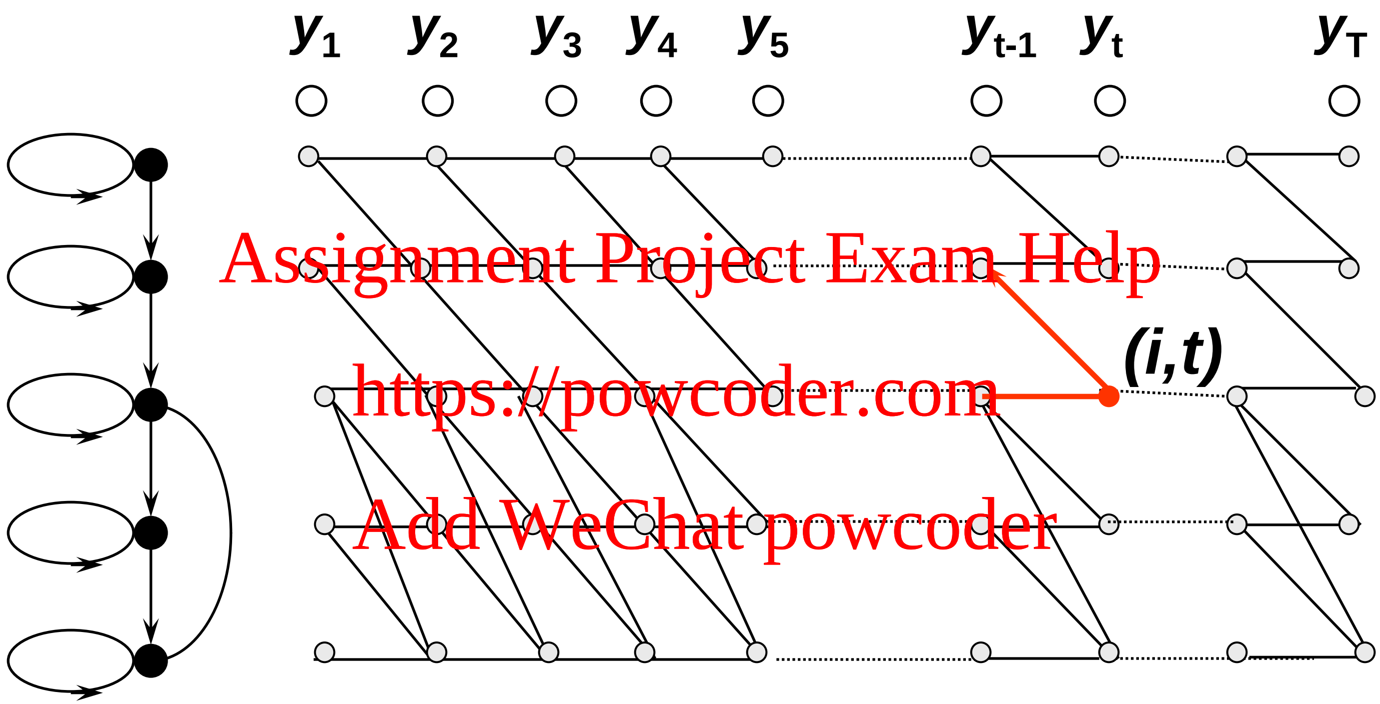
- Let $X = \{x_1, \ldots, x_T\}$ be a state sequence of length T
- The joint probability of Y and X is given by:

$$p(Y, X) = b_{x_1}(y_1) \prod_{t=2}^{T} a_{x_{t-1} x_t} b_{x_t}(y_t)$$

- i.e. the product of the state-output and state transition probabilities along the state sequence

- The <u>optimal</u> state sequence is the sequence X such that $p(Y,X)$ is maximized
- $p(Y)$ is the sum of $p(Y,X)$ over all sequences X

Viterbi Decoding (4)



$$\alpha_t(i) = \text{Prob}(y_1,\ldots,y_t \text{ , opt sequence to } (i,t))$$

$$\alpha_t(i) = \max \{\alpha_{t-1}(i-1)a_{i-1,i} \text{ , } \alpha_{t-1}(i)a_{i,i} \}\, b_i(y_t)$$

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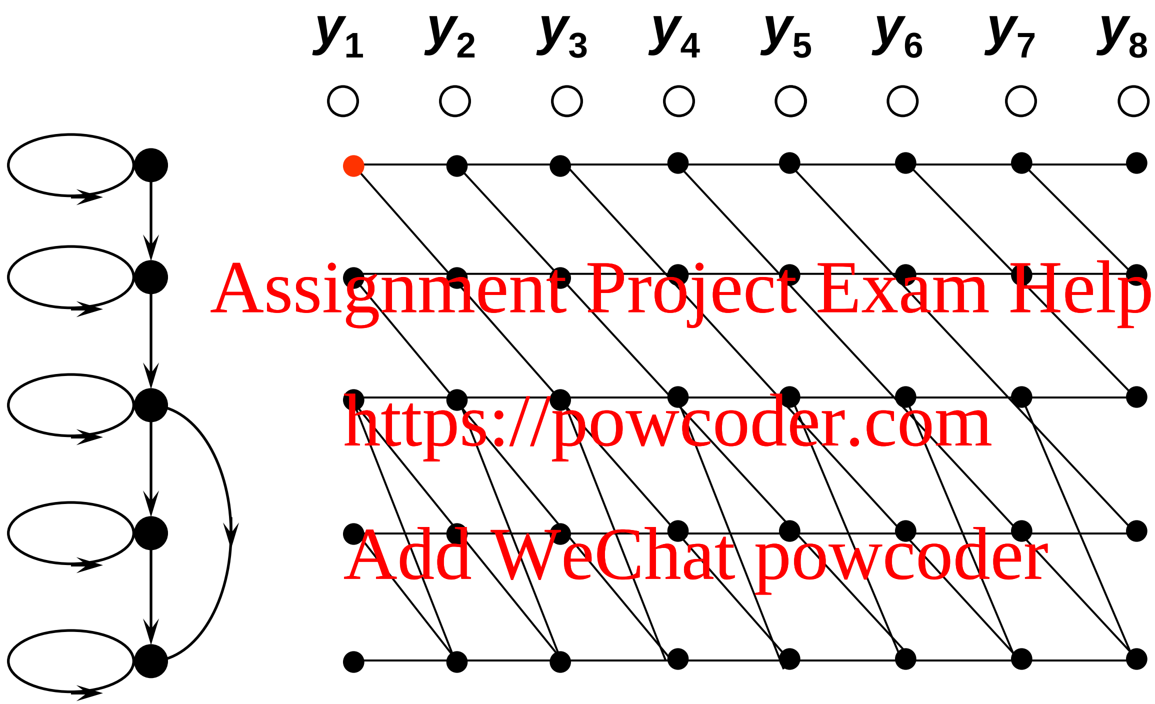
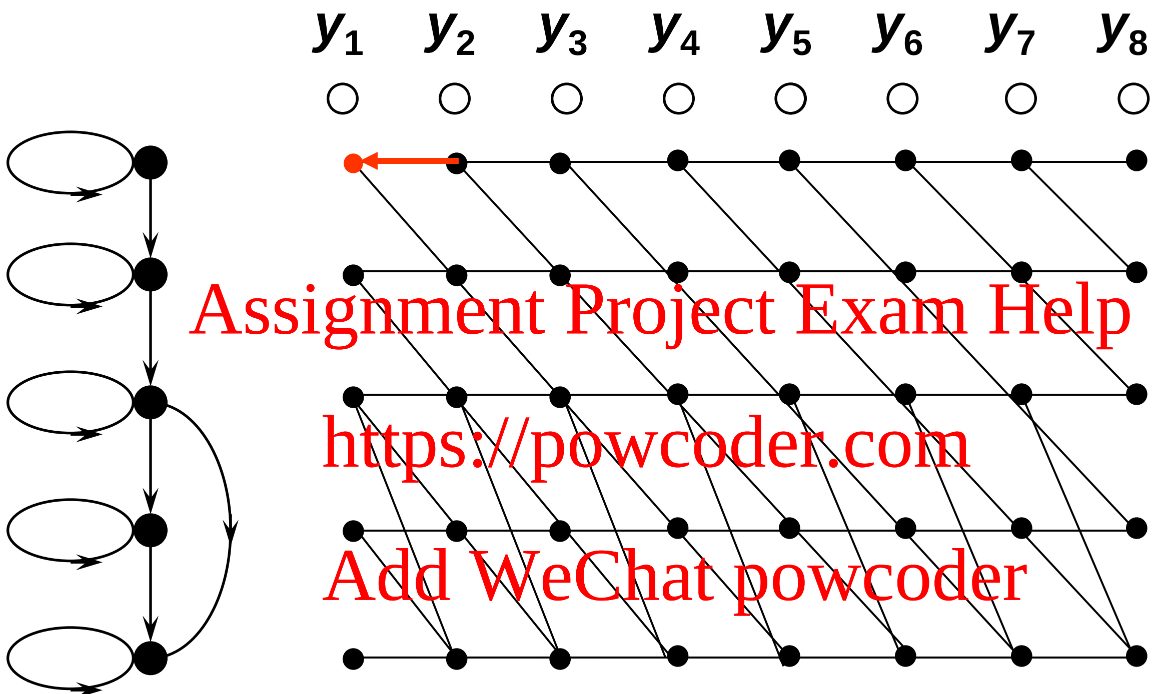
Viterbi Decoding – example



$$\alpha_1(1) = b_1(y_1)$$

Viterbi Decoding – example



$$\alpha_2(1) = \alpha_1(1) a_{11} b_1(y_2)$$

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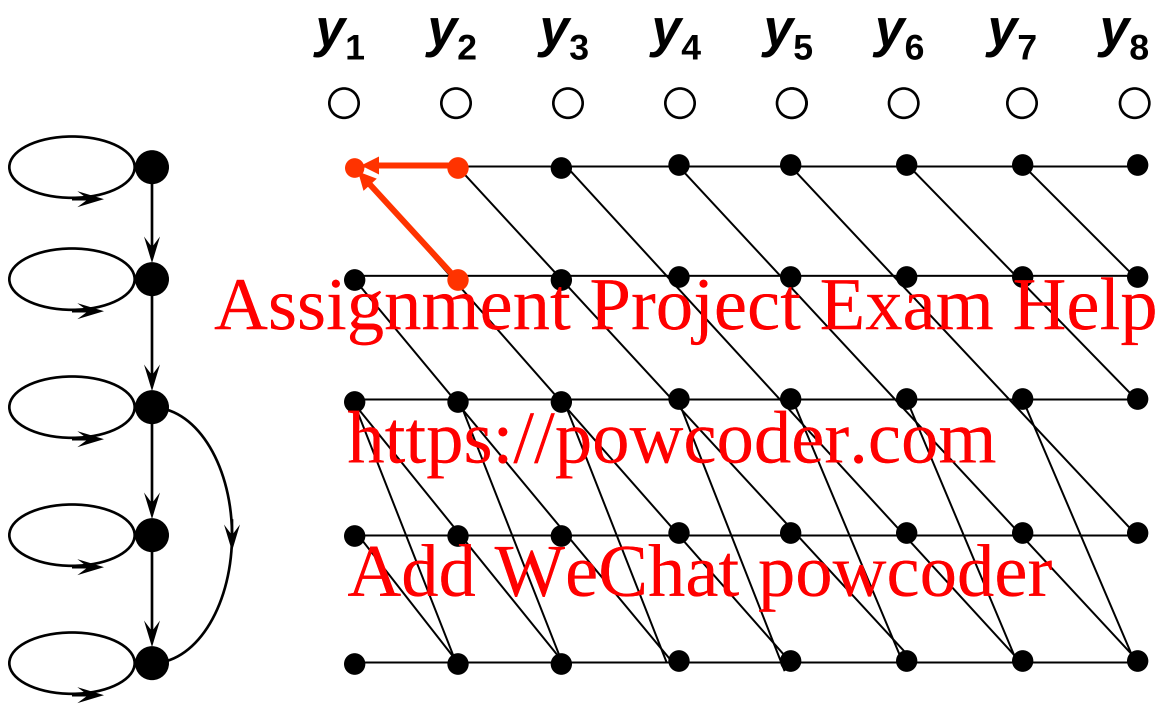
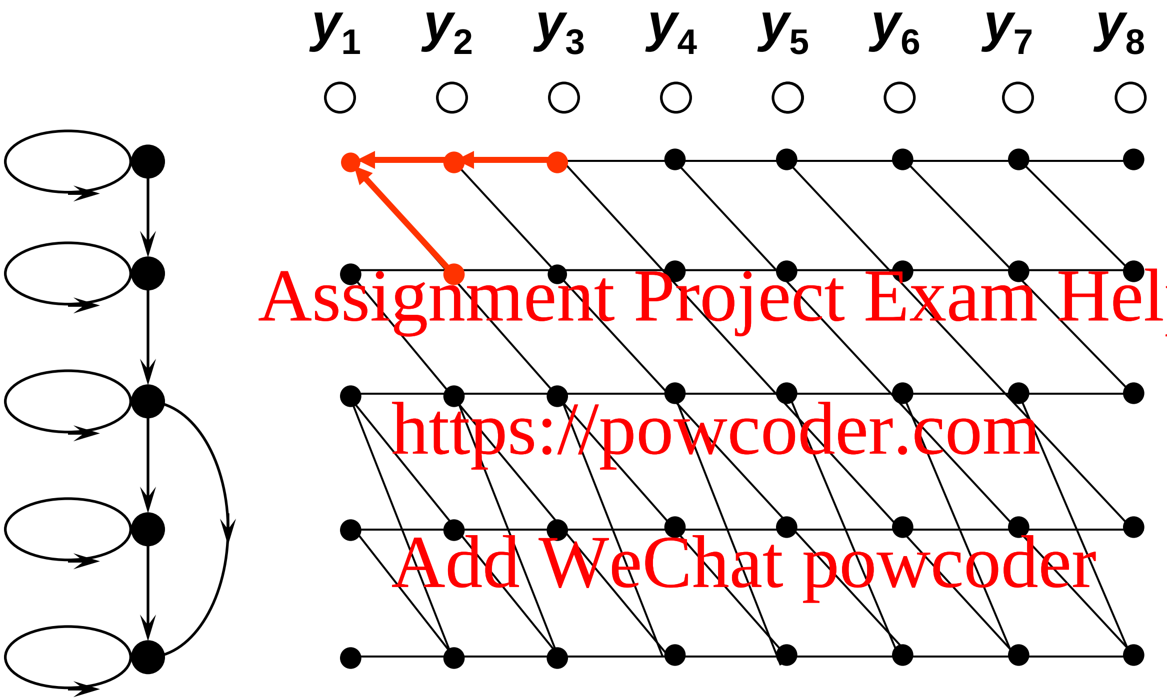
Viterbi Decoding – example



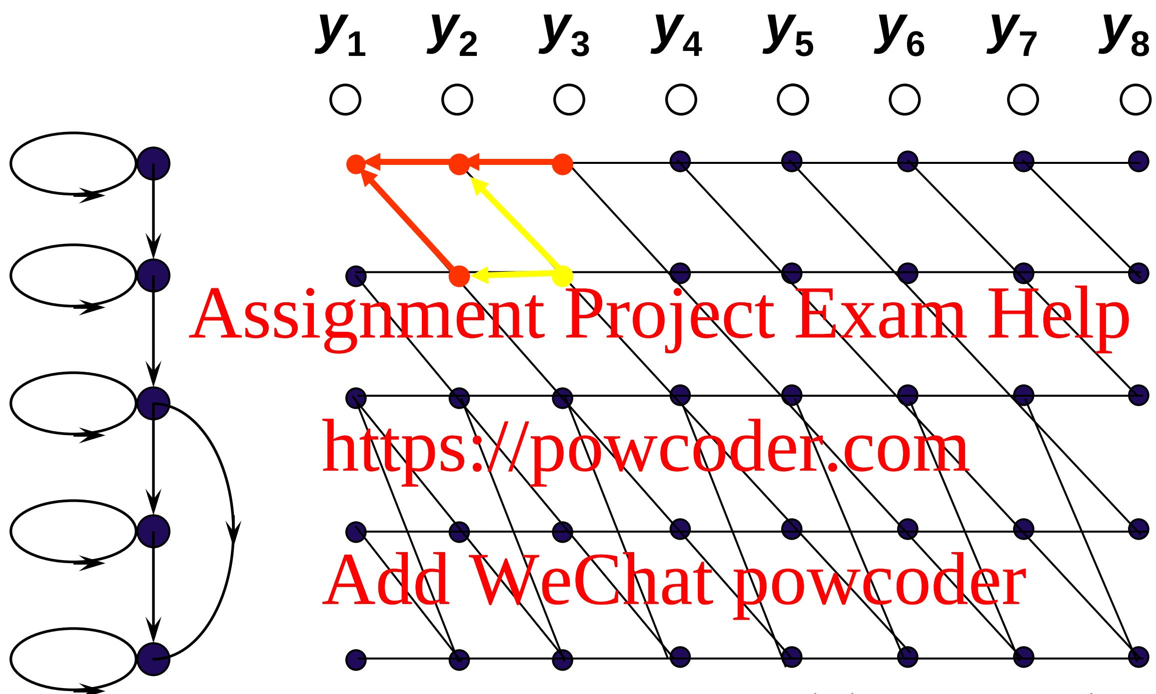
$$\alpha_2(2) = \alpha_1(1) a_{12} b_2(y_2)$$

Viterbi Decoding – example



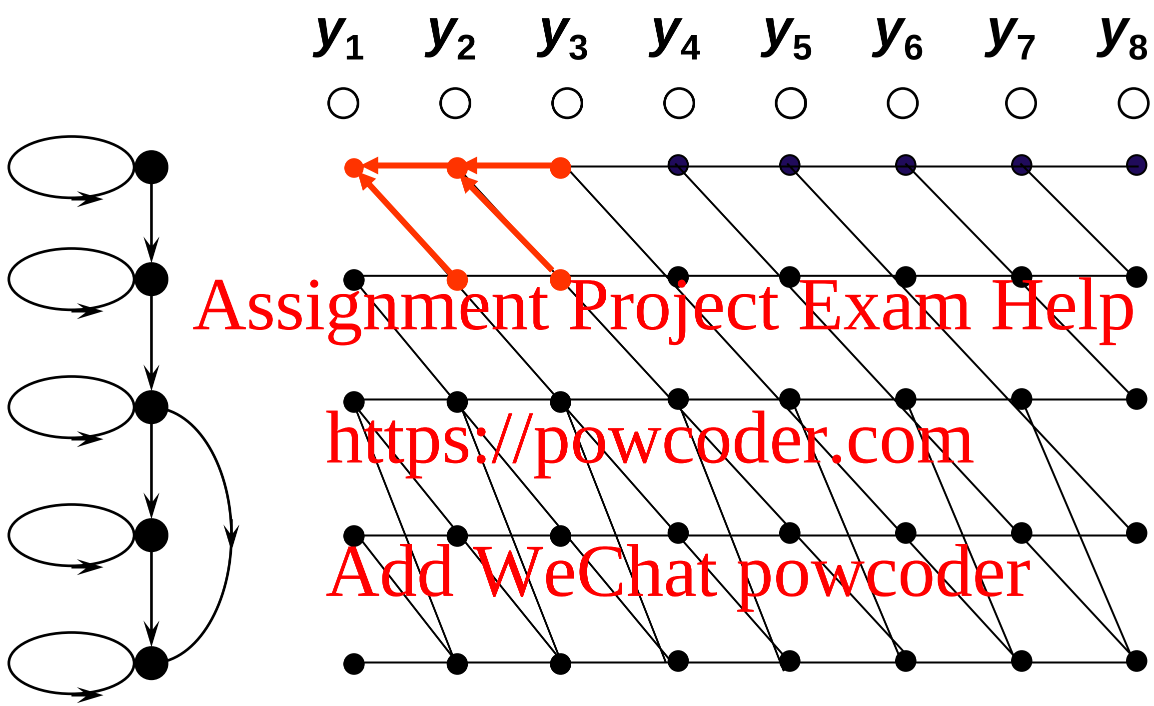
$$\alpha_3(1) = \alpha_2(1) a_{11} b_1(y_3)$$

Viterbi Decoding – example



$$\alpha_3(2) = \max \begin{cases} \alpha_2(1) a_{12} b_2(y_3) \\ \alpha_2(2) a_{22} b_2(y_3) \end{cases}$$

Viterbi Decoding – example



$$\alpha_3(2) = \max \begin{cases} \alpha_2(1) a_{12} b_2(y_3) \\ \cancel{\alpha_2(2) a_{22} b_2(y_3)} \end{cases}$$

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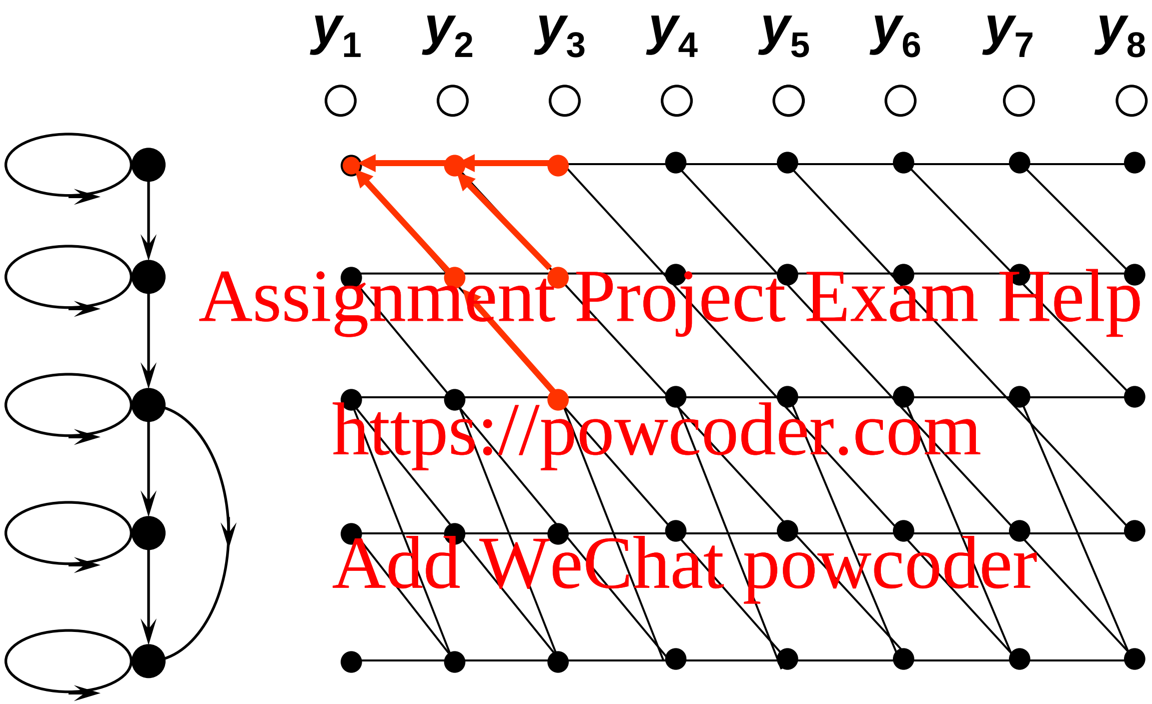
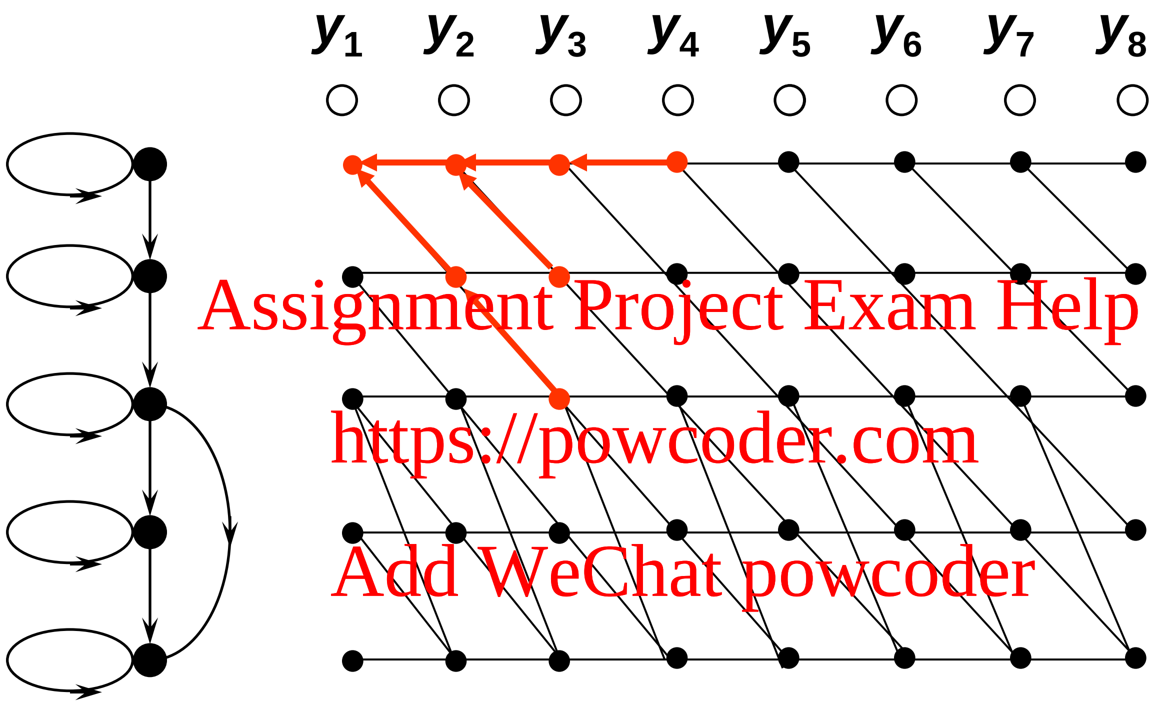
Viterbi Decoding – example

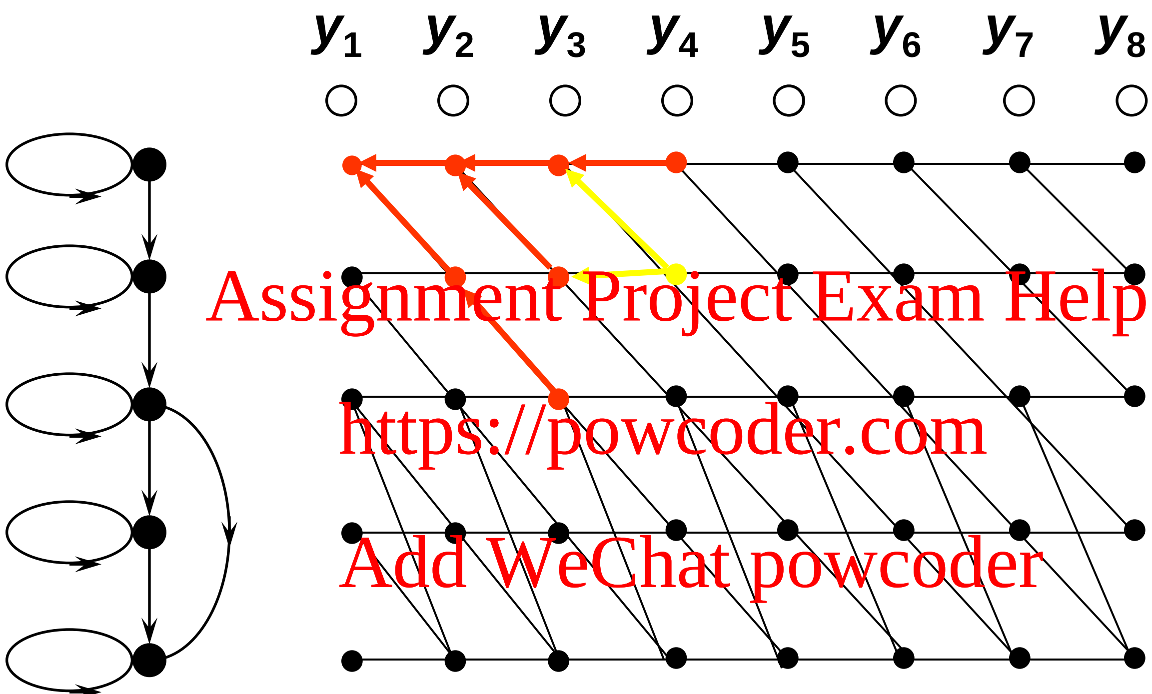


$$\alpha_3(3) = \alpha_2(2)a_{23}b_3(y_3)$$

Viterbi Decoding – example

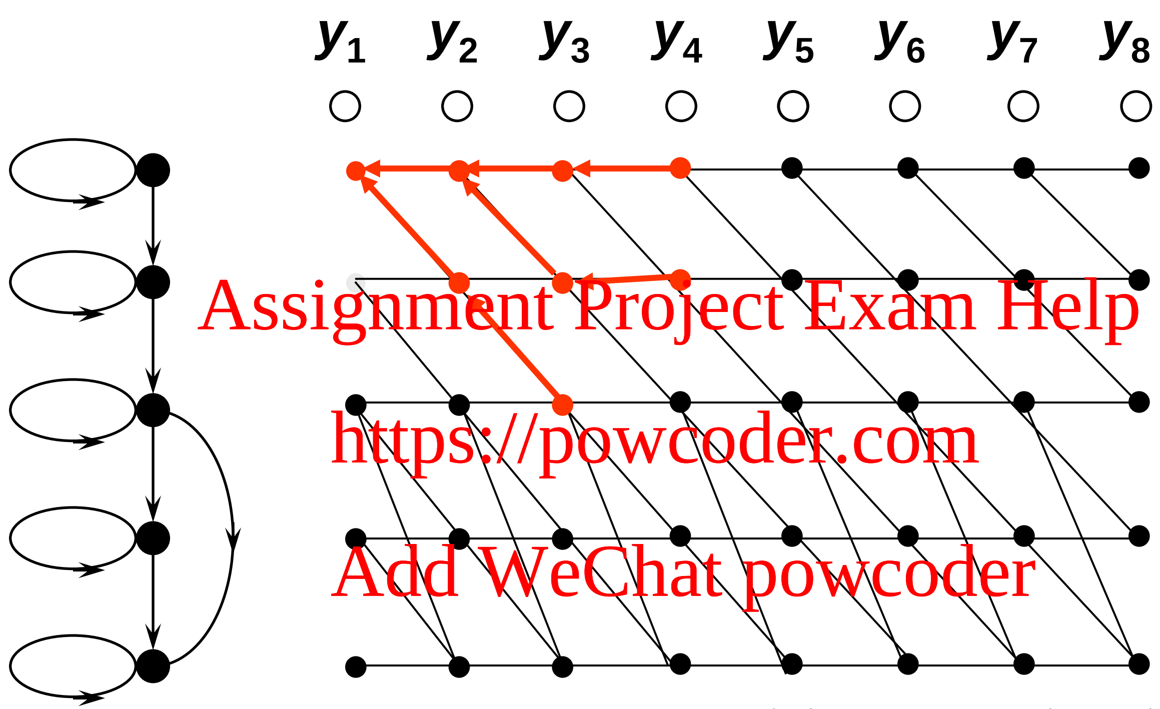


Viterbi Decoding – example



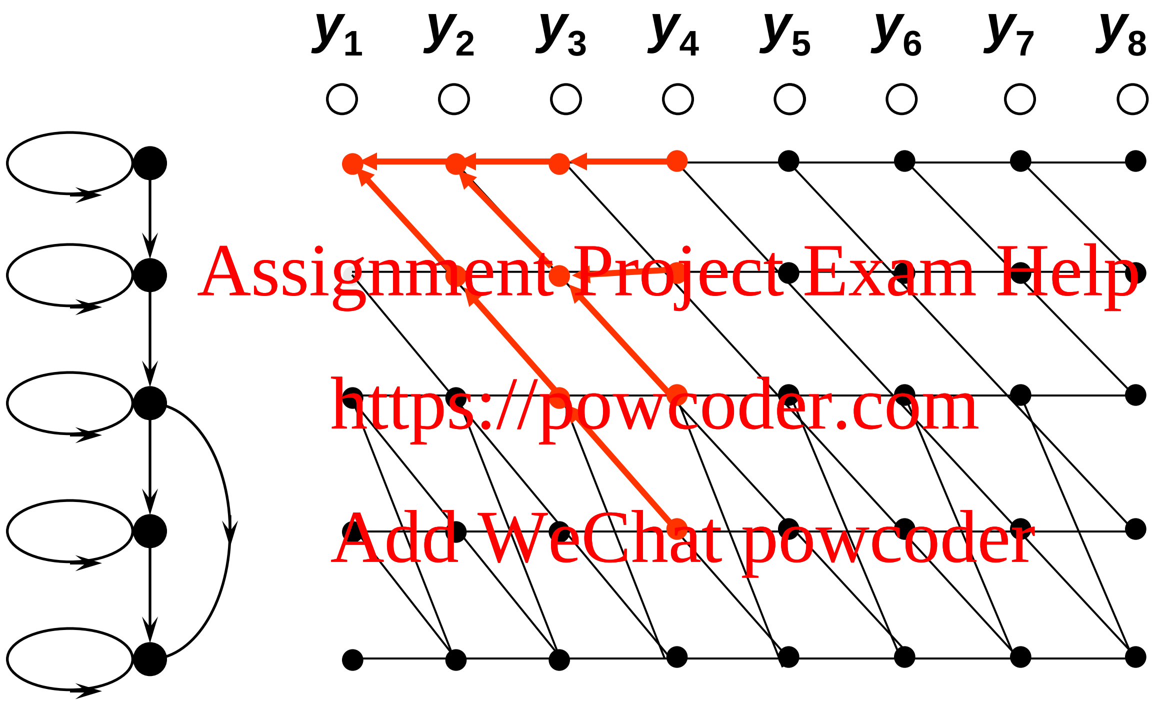
$$\alpha_4(2) = \max \begin{cases} \alpha_3(1) a_{12} b_2(y_4) \\ \alpha_3(2) a_{22} b_2(y_4) \end{cases}$$

Viterbi Decoding – example

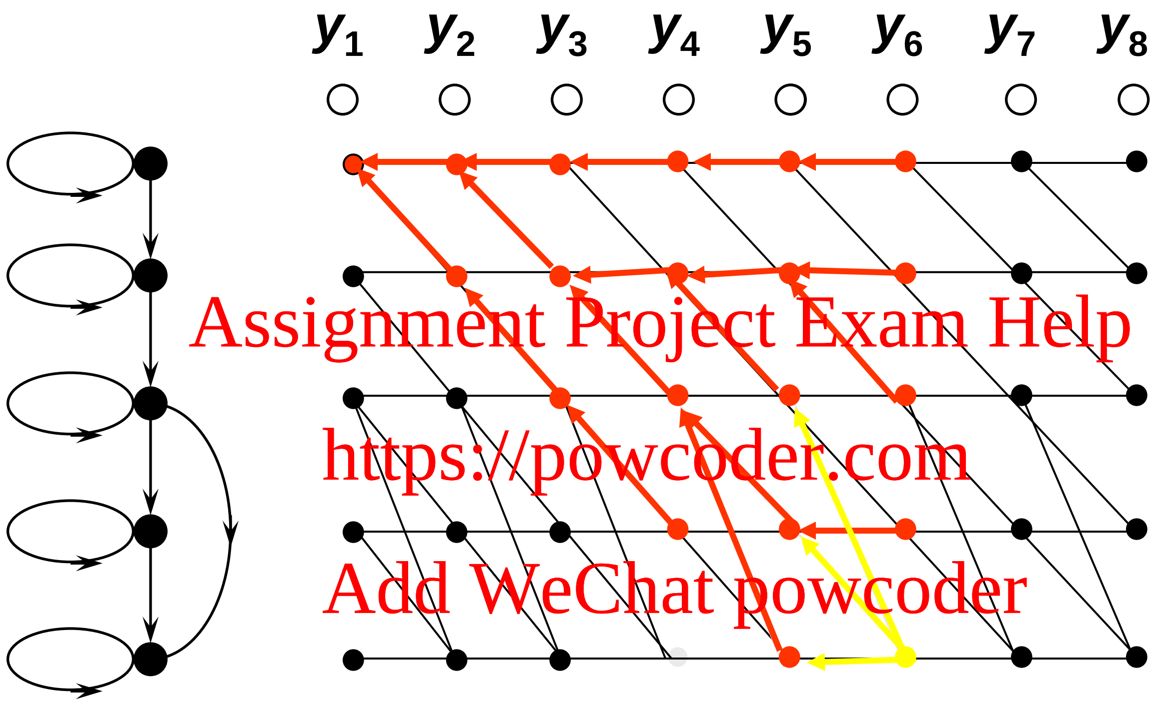


$$\alpha_4(2) = \max \begin{cases} \cancel{\alpha_3(1) a_{12} b_2(y_4)} \\ \alpha_3(2) a_{22} b_2(y_4) \end{cases}$$

Viterbi Decoding – example

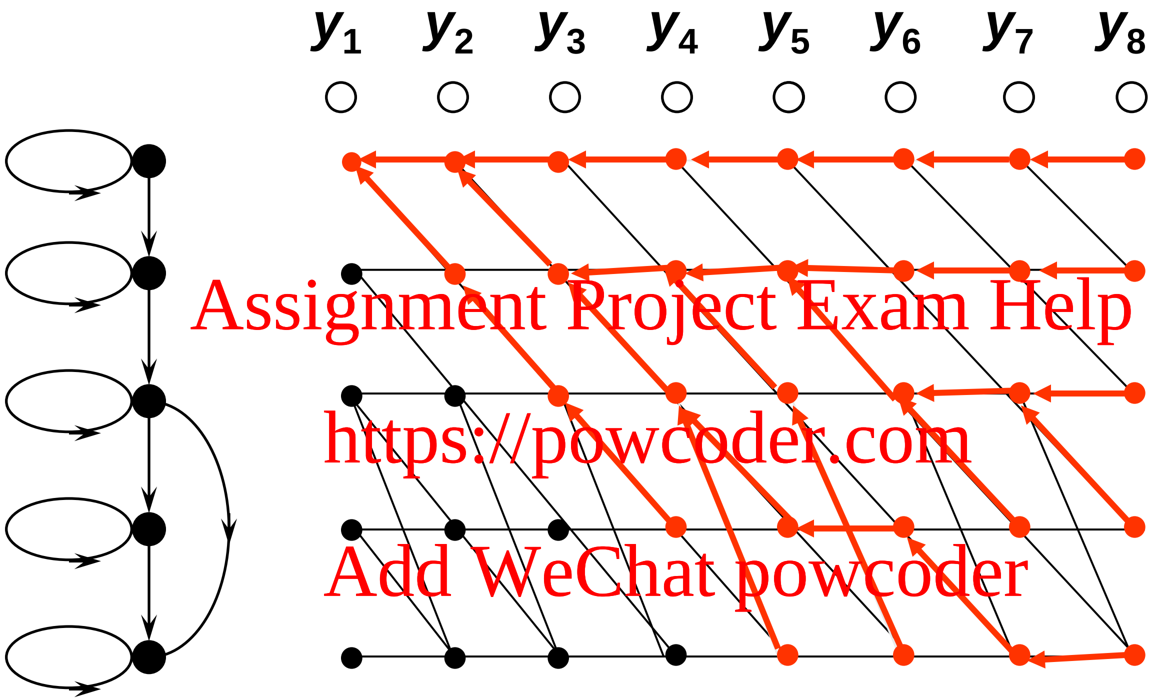


Viterbi Decoding – example

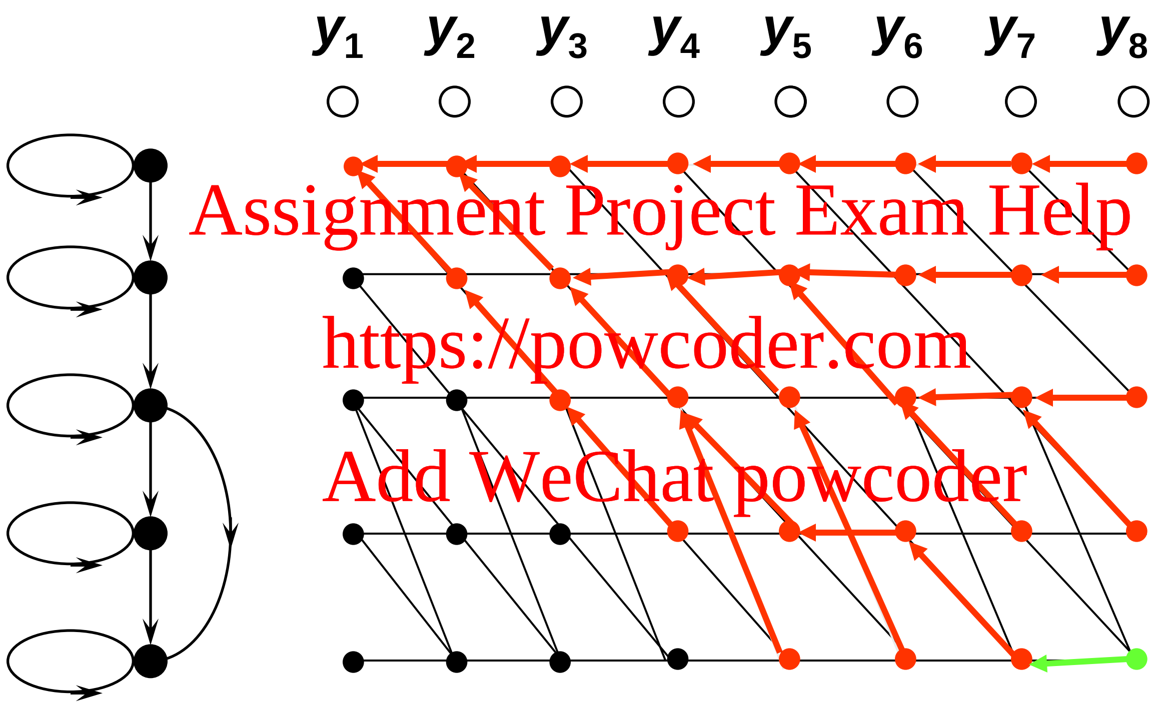


$$\alpha_6(5)=\max\begin{cases}\alpha_5(5)a_{55}b_6(y_6)\\ \alpha_5(4)a_{45}b_6(y_6)\\ \alpha_5(3)a_{35}b_6(y_6)\end{cases}$$

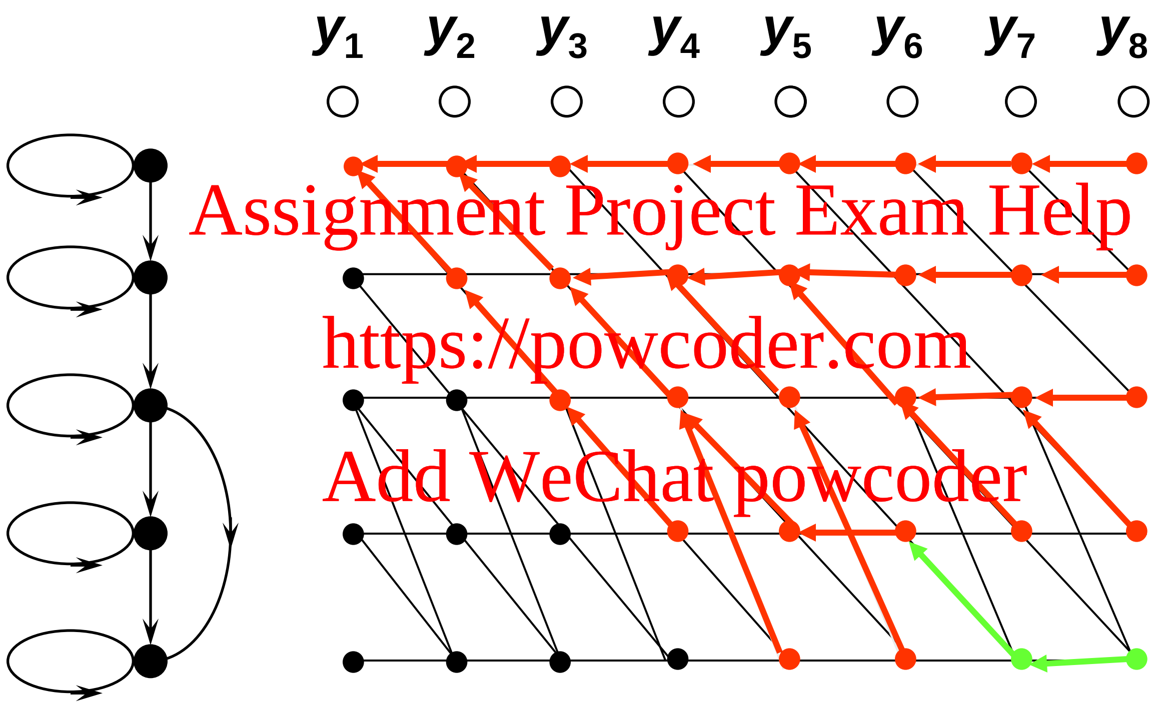
Viterbi Decoding – example



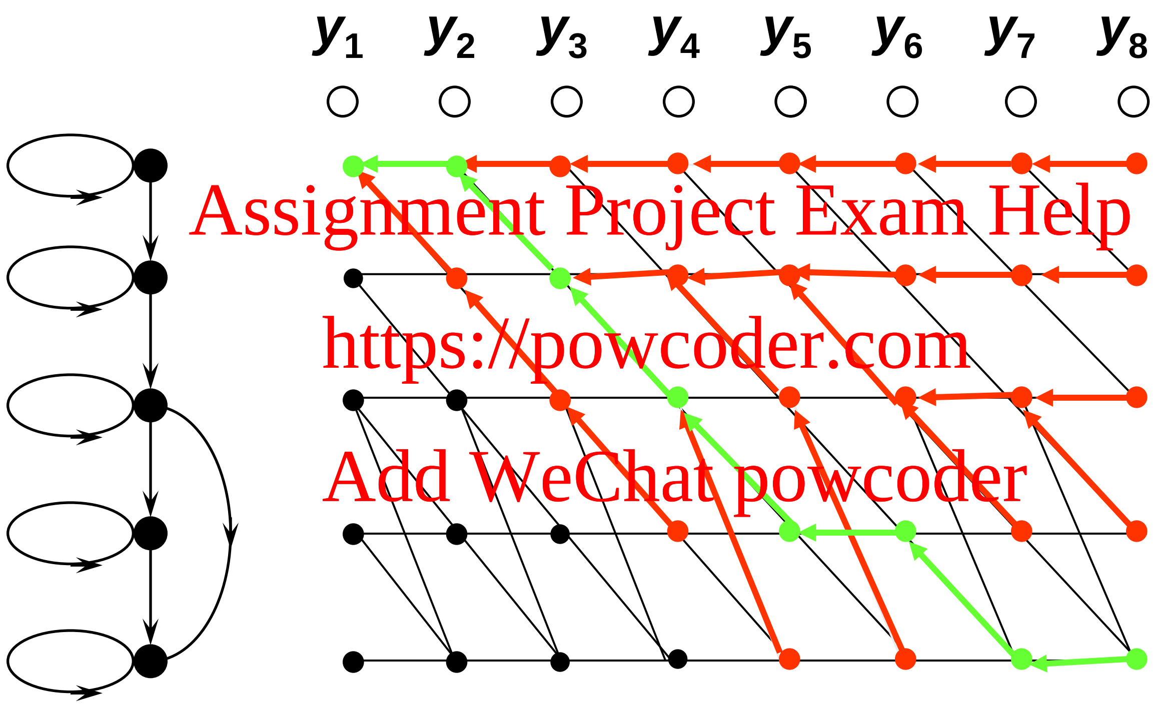
Viterbi Decoding – Trace-back



Viterbi Decoding – Trace-back



Viterbi Decoding – Trace-back



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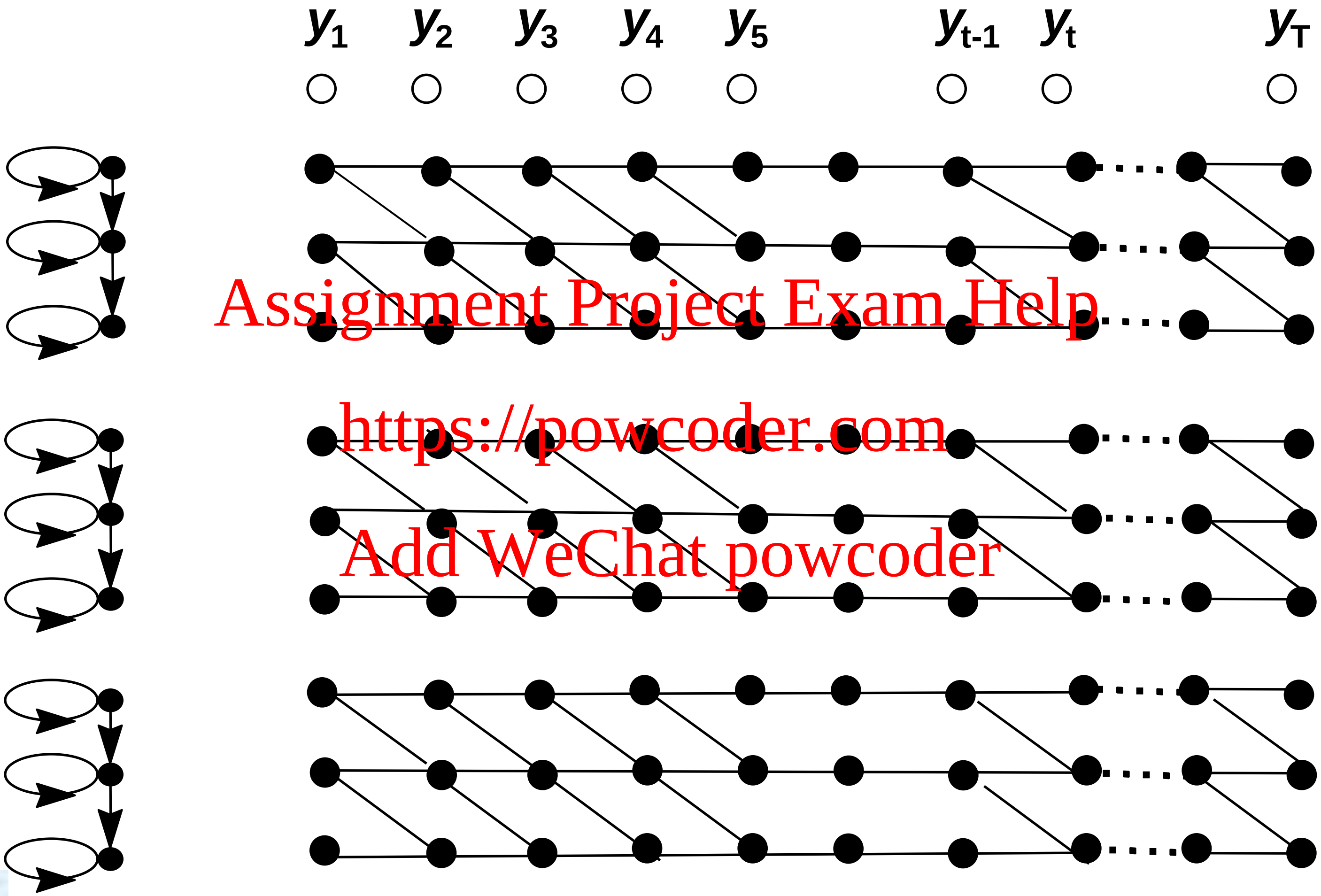
Isolated Speech Recognition



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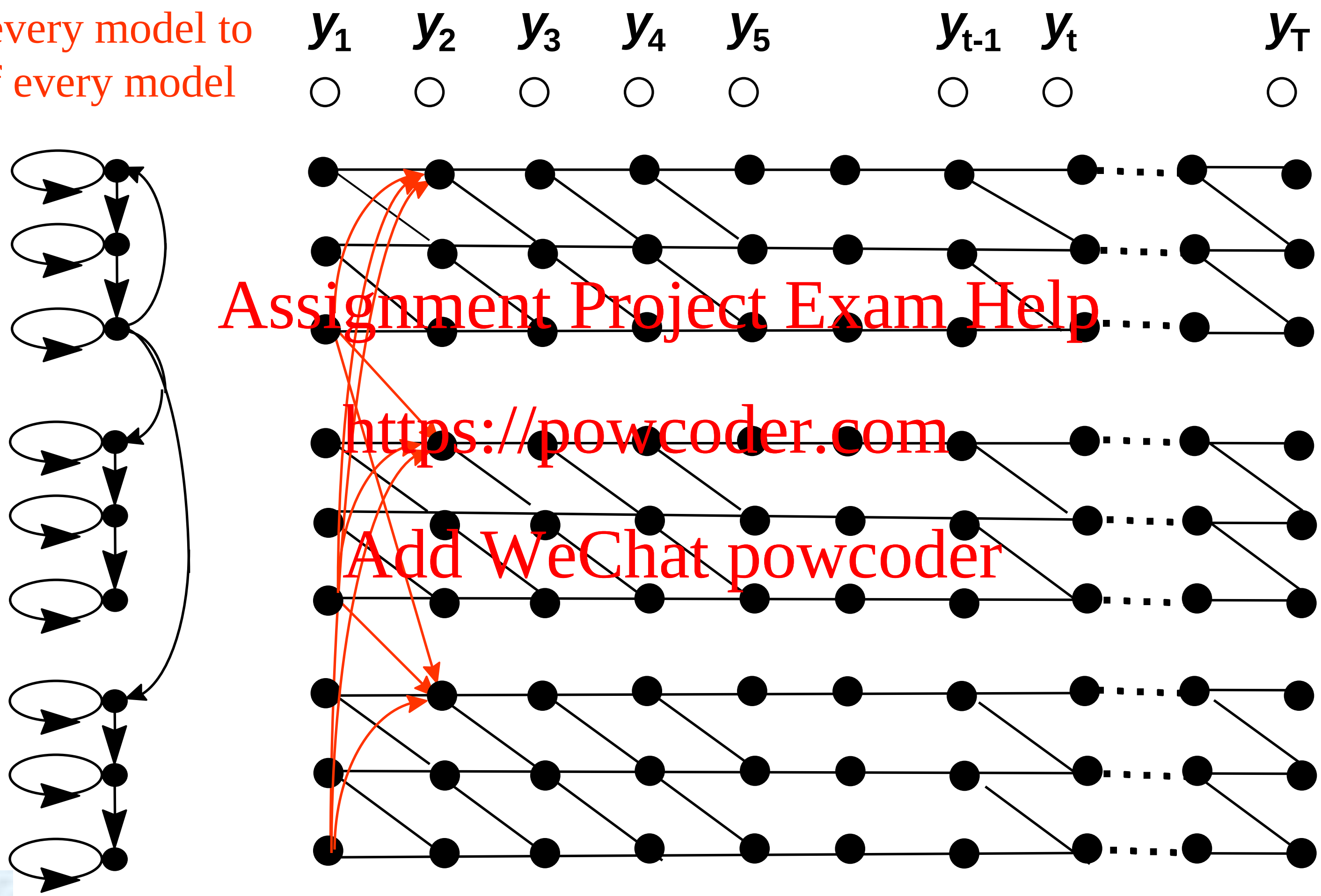
Connected Speech Recognition

New transitions connect end of every model to start of every model



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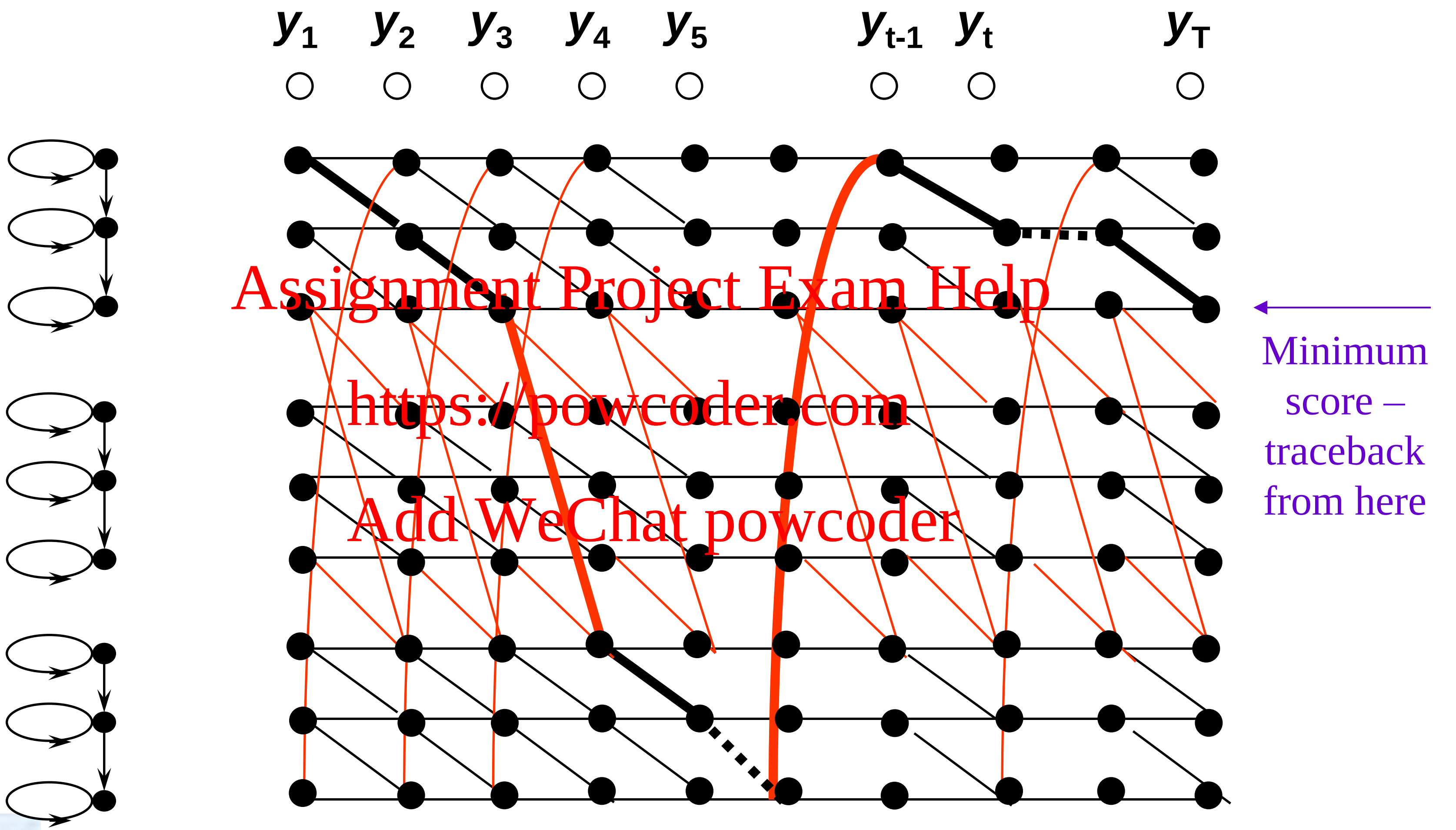
Connected Speech Recognition



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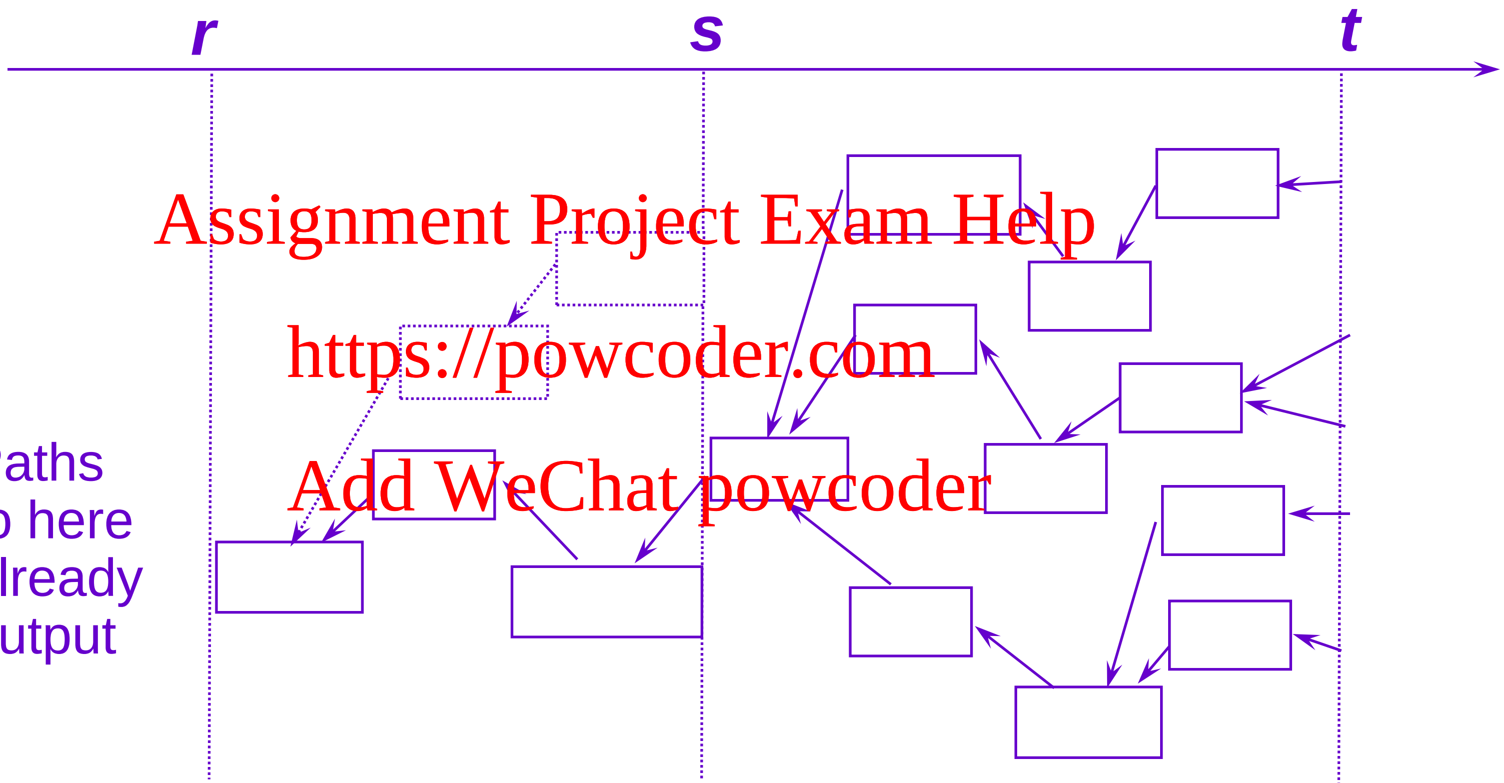
Partial Traceback (1)

- In continuous speech recognition, cannot trace-back from the end of the utterance (there is no end!)
- Instead **partial traceback** operates as follows:

  - For each time *t* and state *i* a *word link record* describes the sequence of words on the best path to *(t,i)*.

  - At regular intervals all active paths are traced back to see if they converge at some time *s* in the past
  - If so, the best path up to time *s* cannot change, and the sequence of words up to *s* can be output

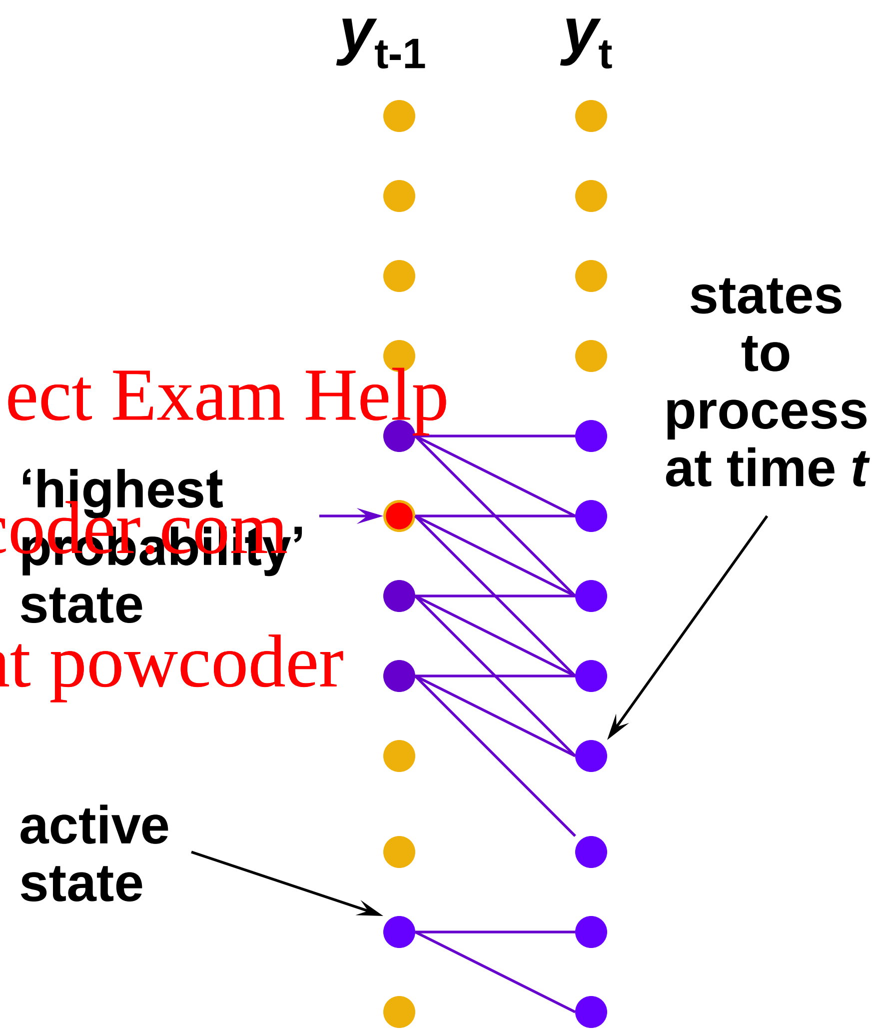
Partial Traceback (2)



Paths
to here
already
output

Beam Pruning

- Choose threshold T
- The active states at time $t\text{-}1$ are those whose partial path scores are within T of the best path score at time $t\text{-}1$
- At time t, only process those states which link back to an active state



Partial Traceback, Beam Pruning & Recognition ‘Speed’

- Partial traceback introduces a ‘lag’ into recognition process - **not** due to inadequate processor speed
- Lag worse when models are poor
- Beam Pruning less effective for ambiguous input
- Severe Beam Pruning will degrade performance
- Proper management of Partial Traceback and Beam Pruning is essential for optimal performance

Summary

- Speech recognition using HMMs
  - Viterbi decoding
  - Isolated & Connected/Continuous speech recognition
  - Beam pruning
  - Partial traceback