4 Spike time-dependent plasticity

This exercise is to study and understand in principle at the level of individual spikes how it makes an influence in synaptic plasticity and also focus on changes in the synaptic efficacy that are driven by temporal correlations between presynaptic spike arrival and postsynaptic firing.

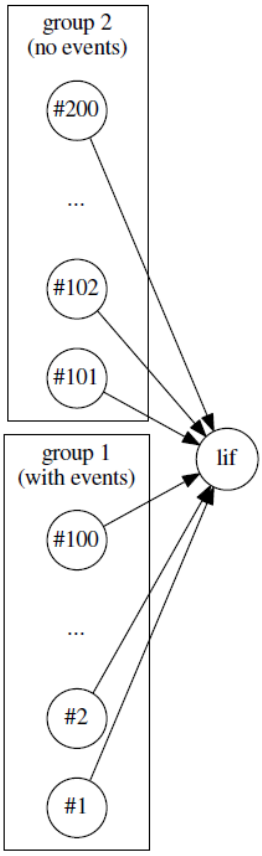

Figure 1: Network architecture.

The model which is being used for the assignment consists of two groups of 100 neurons each which spike randomly (background firing). Neuron within the first group also receive additional input which triggers special events (synchronized or sequential firing of all neurons in the group). These input neurons are connected to a single LIF neuron via plastic synapses with STDP. During the task it was made an investigation about the changes of the weights of two groups of input neurons over time.

Synapse model

In the following we develop a Synapse model for spike-time dependent synaptic plasticity. We assume that apart from an activity-independent weight decay all changes are triggered by pre or postsynaptic action potentials. For the sake of simplicity- and for want of detailed knowledge we take weight changes

to be instantaneous, i.e., the synaptic efficacy is a piece-wise continuous function depends on the relative timing of previous spikes and the current weight which is computed by

$$\Delta W(\Delta t, w) = \begin{cases} \lambda\,(1-w)^{\mu_+}\,\mathrm{e}^{-|\Delta t|/\tau_+} & \text{if } \Delta t \geq 0 \\ -\lambda\,\alpha\,w^{\mu_-}\,\mathrm{e}^{-|\Delta t|/\tau_-} & \text{if } \Delta t < 0 \end{cases}, \tag{1}$$

where

τ_+ and τ_- are time constants governing the width of the learning window. μ_+ and μ_- determine the weight dependency of the update, α sets the shape of the depression part relative to the facilitation part, and λ is a learning rate.

Task 4a

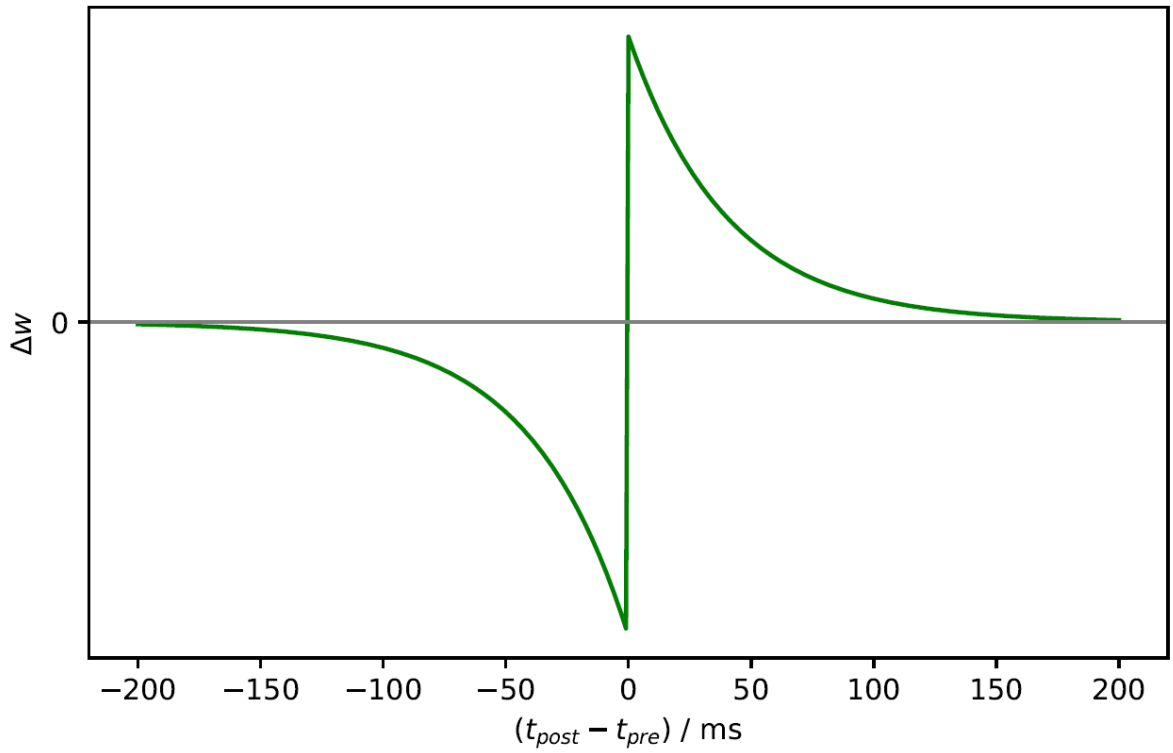

Figure 1

Fig 1 illustrates the two-phase learning window Δw as a function of the time difference $\Delta t = (t_{post} - t_{pre})\ /\ ms$ between presynaptic spike arrival and postsynaptic firing with $\mu_+ = \mu_- = 0$ and a learning rate of $\lambda = 0.005$. The time constants should be $\tau_+ = \tau_- = 40$ms. Furthermore, initial weight values of $w_0 = 2000$ pA for all synapses and maximum weight values of $2.w_0$.

Each spike that arrives at the presynaptic terminal can trigger a change in the synaptic efficacy even without additional postsynaptic action potentials. The value of $\lambda(1-w)^{\mu_+}e^{-\frac{|\Delta t|}{\tau_+}}$ if $\Delta t >= 0$ from (1) gives the weight change if a presynaptic spike arrival is earlier than postsynaptic action potential with delay Δt and other way round with $-\lambda\alpha w^{\mu_-}e^{-\frac{|\Delta t|}{\tau_-}}$ if $\Delta t < 0$ from (1).
Synaptic changes Δw occur only if presynaptic firing t_{pre} and post synaptic activity at t_{post} occur sufficiently close to each other. A positive change (LTP) occurs if the presynaptic spike precedes the postsynaptic one; for a reversed timing, synaptic weights are decreased(LTD). The resulting change in the synaptic efficacy Δw after several repetitions of the experiment turns out to be a function of the spike differences $(t_{post} - t_{pre})$ ('spike time dependent synaptic plasticity'). Most notably, the direction of the change depends critically, i.e. on a millisecond time-scale, on the relative timing of pre and post-synaptic spikes. The synapse is strengthened if the presynaptic spike occurs shortly before the postsynaptic neuron fires, but the synapse is weakened if the sequence of spikes is reversed. The observation is that the presynaptic neurons that are active slightly before the postsynaptic neuron ae those which 'take part in firing it' whereas those that fire later obviously did not contribute to the postsynaptic action potential. The direction of the weight change depends on the sign of the expression in the equation (1). And the parameters such as τ_+, τ_-, μ_+, μ_- and α play a key role in learning mechanism with which two phase learning curve gets improvised.

Task 4b

In this task, as per the model details, all neurons generate spikes according to Poisson processes with a constant rate $r_{background}$ = 8Hz. And Neurons in the first group additional fire in an organized fashion i.e. all neurons in the group will fire at the same time when event occurs (Poisson processes with a constant rate r_{event} = 2Hz). With respect Group2 as it can be observed that the amplitude of the pulses is not strong enough because of the frequency of spike train which evokes no Long-term Potentiation (LTP) at Group2 synapses. But however, because of the spike fire of all neurons from Group 1 which is caused by an event which occurs at rate 2Hz, the synaptic efficacy of Group1 synapses as a result from the Group 1 neurons there is a slight contribution toward the improvement of postsynaptic membrane potential. Having had the initial synaptic efficacy of 2000pA. From the Group 1 point of view i/i correlations if considered, since there was spike fire generated every 2Hz from the neurons as, per the Hebbian's rule of cooperativity the group 1 neurons are strengthened eventually. This leads to LTP of Group 1 synapses. It is consistent when $\Delta t > 0$,

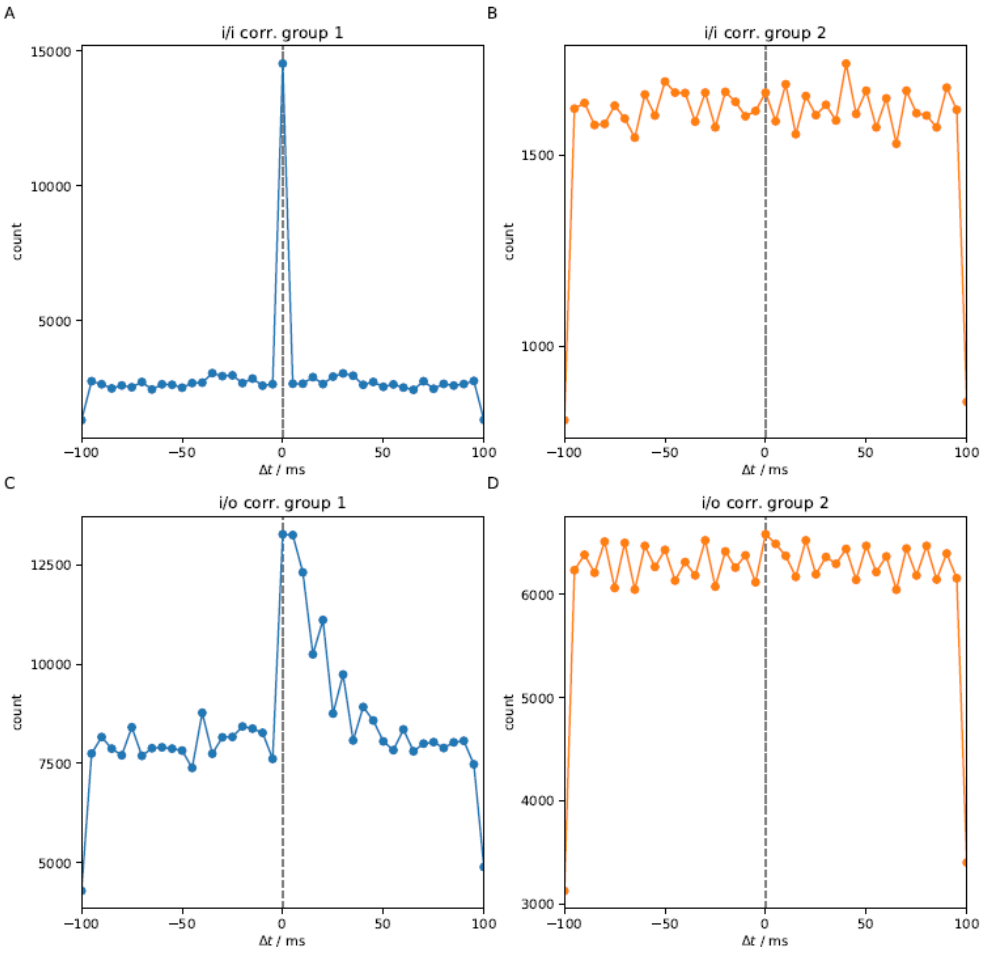

Figure 2.1

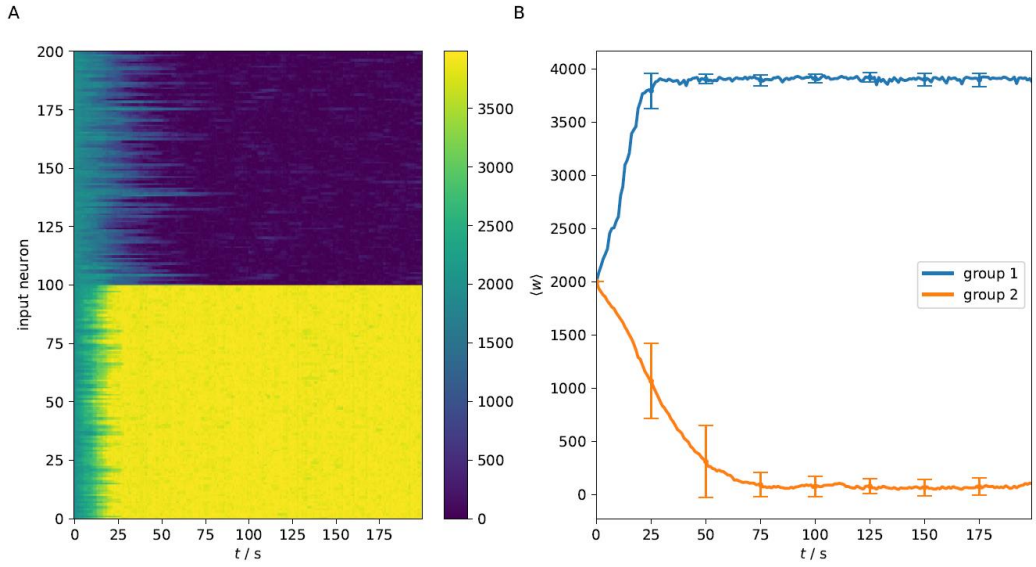

Figure 2.2

When $\Delta t = 0$, it can be seen there's a rapid generation of spikes due to which the synaptic efficacies would have drastically improved because there is a maximum contribution towards the postsynaptic membrane potential. Then gets back to its earlier efficacies and gradually Δt tends to become < 0 where even though the frequency at which the spikes are generated are high enough to cause the LTP but just because it is after the postsynaptic potential it is not much

contributing toward the growth of it, yet the LTP is at very minimal range and that's how stabilizes.
From the Group 1 point of view i/o correlations, as long as $\Delta t > 0$ there's a significance in LTP of Group 1 synapses which is contributing towards the growth of postsynaptic membrane potential. But when Δt tends to becomes < 0, it is expected to cause LTD but however because of the frequency at which the spikes are coming it still manages to have LTP at minimal range.
From the Group 2 point of view i/i correlations, firstly because of due to the frequency the spikes are generated, it is not strong enough to cause LTP but LTD. Yet, because of the random processes of the spikes sometimes the spike from one input neuron maybe near close to spike of another input neuron which can helps to have LTP of group 2 synaptic weights to some amount. And also, from the influence of Group 1 growth in synaptic efficacies, there could be a mutual growth in Synaptic efficacies of Group 2 neurons but it keeps fluctuating but it would be more inclined to have LTD of weights.
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From the Group 2 point of view i/o correlations, in terms of Δt it is exact behaviour just as explained with Group 1 but with different polarity that is instead of having LTP it is LTD all the time.

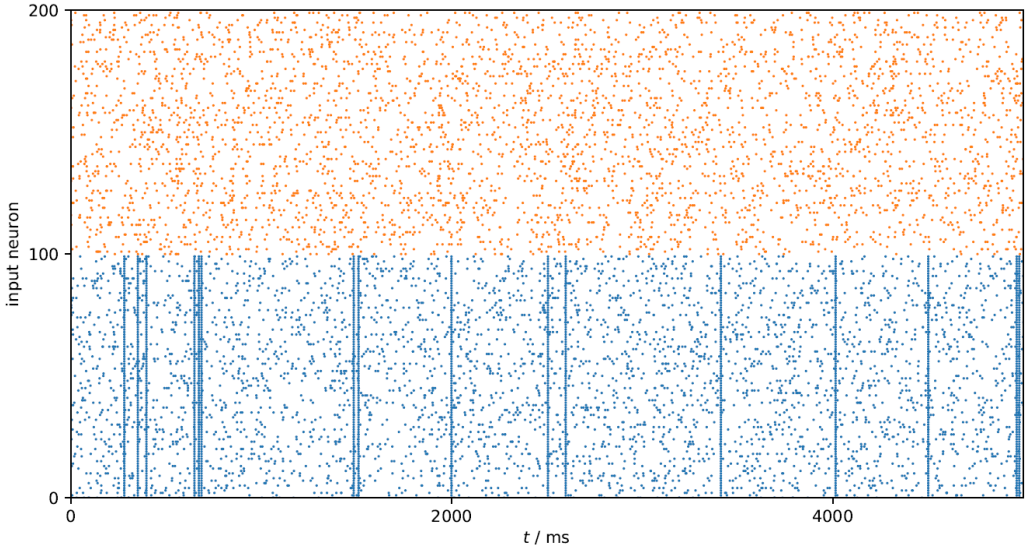

Figure 2.3

Task 4c

In this task, as per the model details, all neurons generate spikes according to Poisson processes with a constant rate $r_{background}$ = 8Hz. And Neurons in the first group additional fire in an organized fashion i.e all neurons in the group will fire at the same time when event occurs (Poisson processes with a constant rate r_{event} = 2Hz). But with the additional jitter of 5ms and 15 ms. In principle, the dynamics of weight changes are as described in the previous task but when it is subjected to jitter of few units, there can be a slighter impact on the dynamics of the weight changes.

Let's consider when Jitter = 5ms it can be observed that there is a disturbance in LTP or LTD of Synaptic weights.
From the point i/o correlation Group1 and Group 2 views there is upside down in spikes generation because of the standard deviation it has got in terms of spike arrival with respect to postsynaptic action potential. Resultant to which sometimes the deviation between spike from one neuron is lesser and some other time it is greater. As a result, the learning process is slight slower compared to that of not having Jitter

From the point of i/i correlation Group1 and Group2 view there is a variation in spikes generation because of again the standard deviation it has got in terms of spike from one neuron to spike from another neuron. Which is making impact in consistent generation of spikes.

Jitter = 5ms

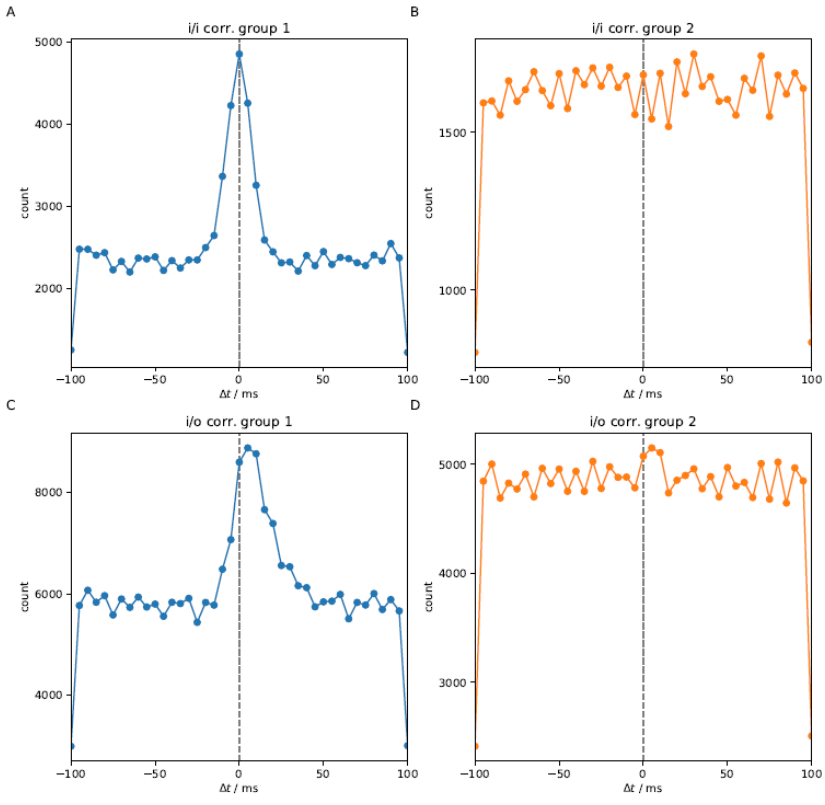

Figure 3.1

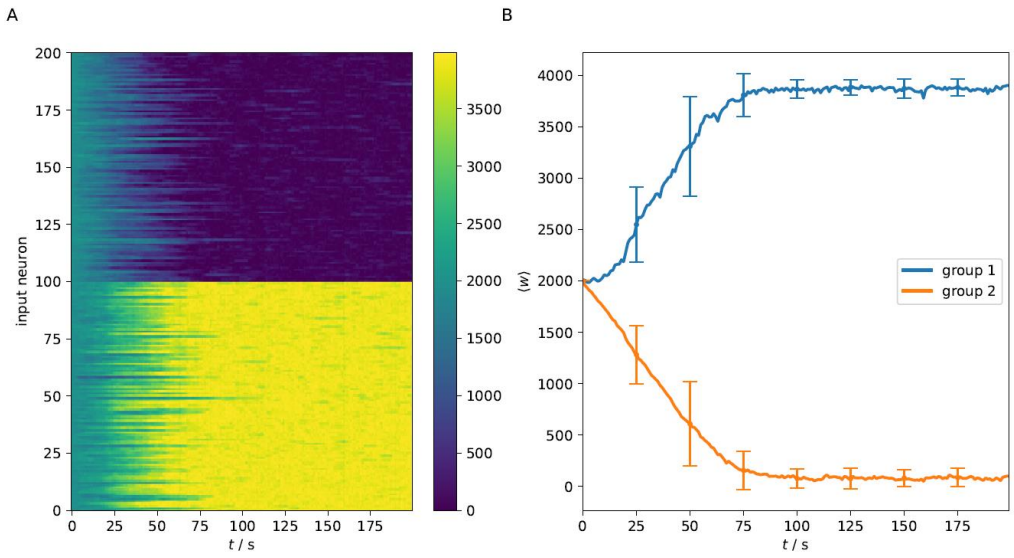

Figure 3.2

And the spikes look like Figure 3.3

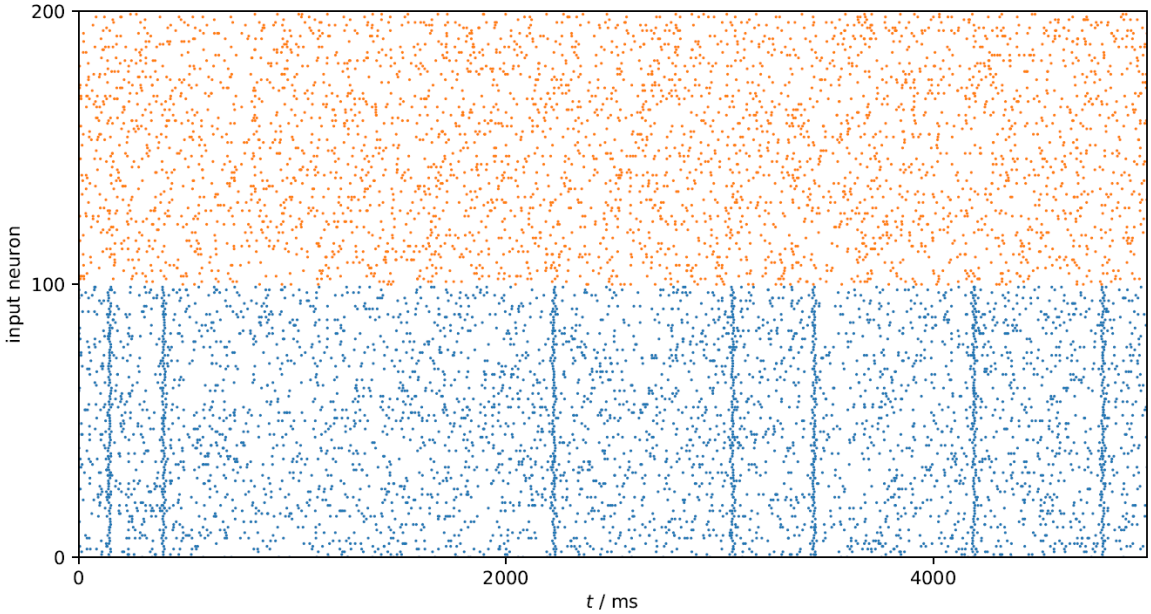

Figure 3.3

Whereas, when Jitter = 15ms it can still be observed that there is a disturbance in LTP or LTD of Synaptic weights. But the disturbance is at the greater side.

From the point i/o correlation Group1 and Group 2 views there is upside down in spikes generation but this time because of the more standard deviation it has got in terms of spike arrival with respect to postsynaptic action potential the deviation between spike from one neuron to other neuron is even more oscillating. As a result, the learning process is gets oscillated.

From the point of i/i correlation Group1 and Group2 view there is a large variation in spikes generation because of again the larger standard deviation it has got in terms of spike from one neuron to spike from another neuron. Which

makes the dynamics little unpredictable and gets more complicated in terms of learning.

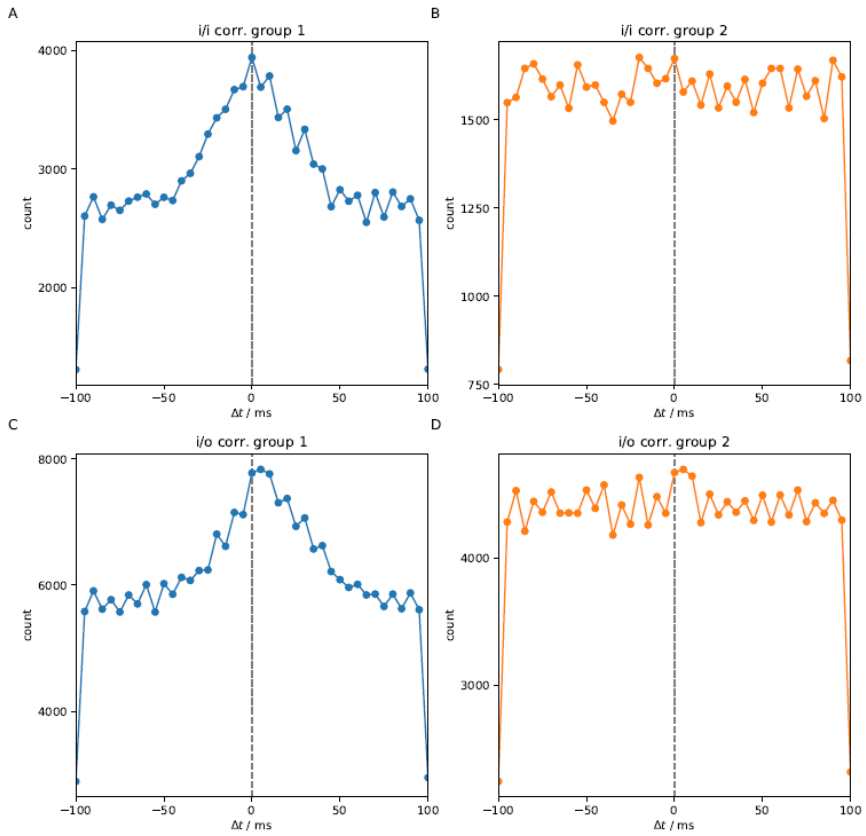

Figure 3.4

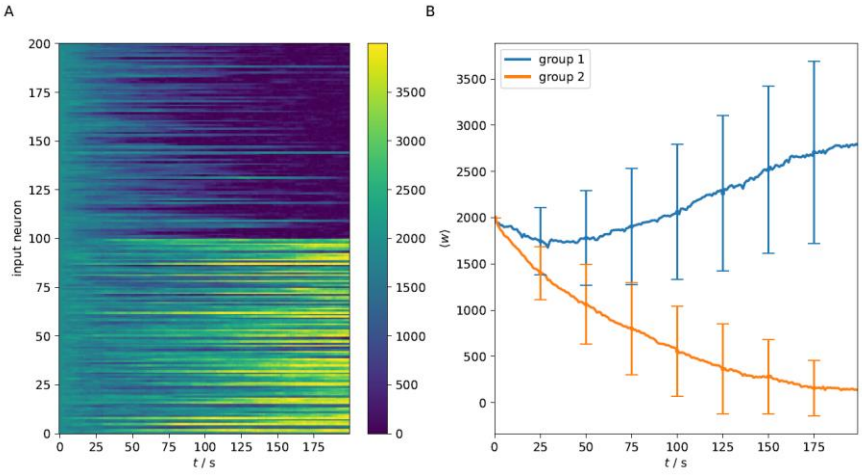

Figure 3.5

And the spikes look like Figure 3.6

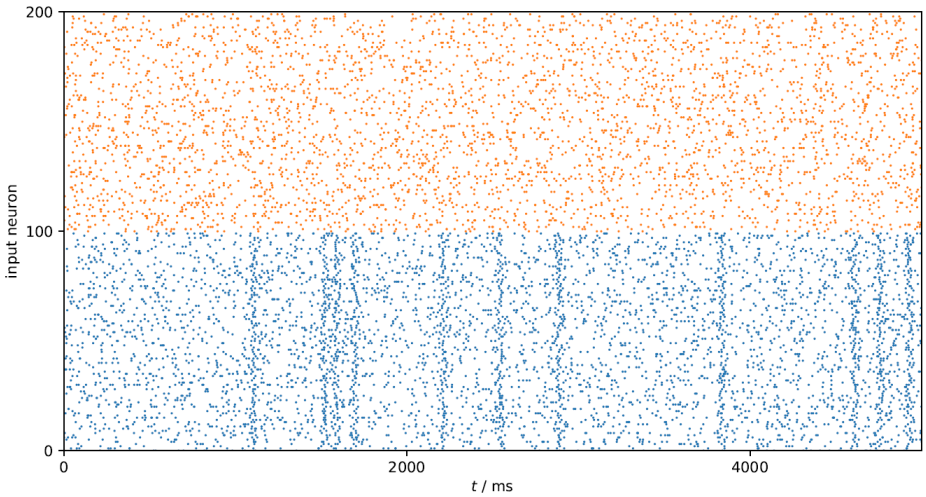

Figure 3.6

Task 4d

In this task, as per the model details, all neurons generate spikes according to Poisson processes with a constant rate $r_{background}$ = 8Hz. And Neurons in the first group additional fire in an organized fashion i.e all neurons in the group will fire at the same time when event occurs (Poisson processes with a constant rate r_{event} = 2Hz). But this time sequence = True and jitter=0 which means that the neurons in the first group first sequentially with a delay of 1ms per neuron whenever there is an event. Delay of 1 ms between the consecutive spikes from the neurons made a slighter contribution towards the LTP of Group1 synaptic weights. But when the same mechanism of spike generation was compared with Group2 it was more prone to have LTD which actually influences Group 1 input neurons to pull towards LTD. When it is observed from the Figure 3.8 alone it can be observed that the spikes which occurred from Group 1 before the postsynaptic potential were all contributing toward the growth of membrane potential however because of the influence of Group 2 neurons the synaptic efficacies altogether are exploited. And also, the spike generation is relatively making less impact than firing in terms of evoking LTP which doesn't let to LTP even at $\Delta t < 0$. But then from the principle once when it reaches the region $\Delta t > 0$, it makes the synaptic efficacies even lesser i.e. LTD.

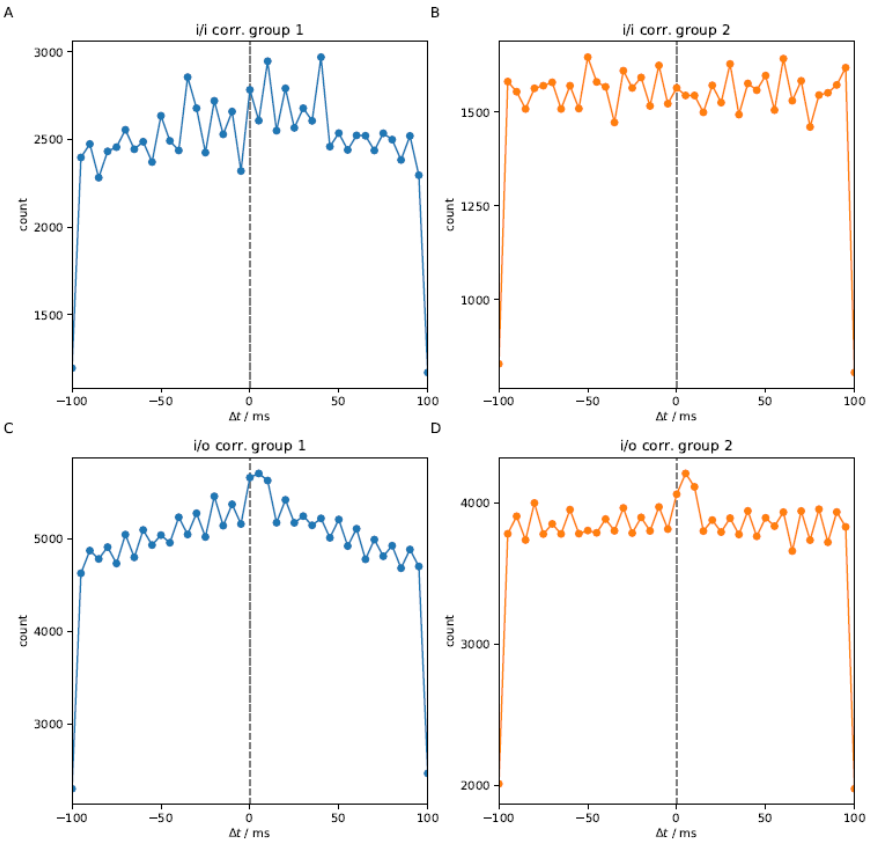

Figure 3.7

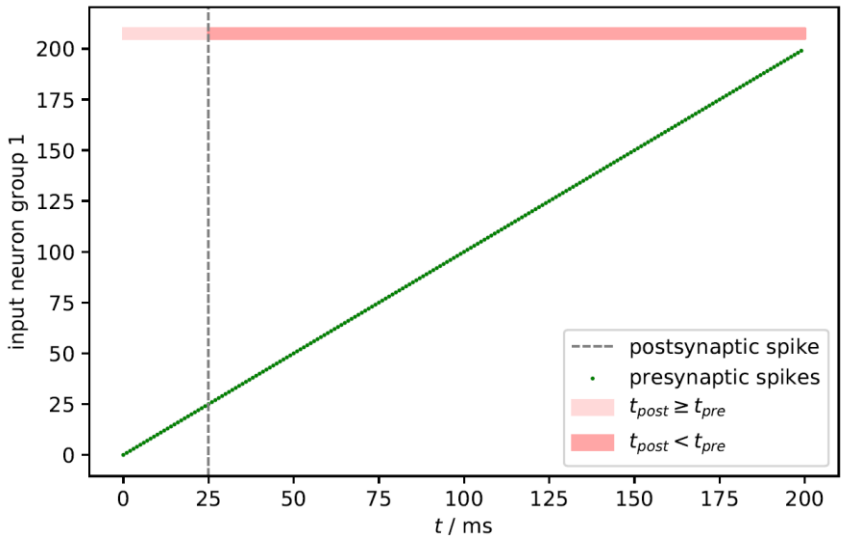

Figure 3.8

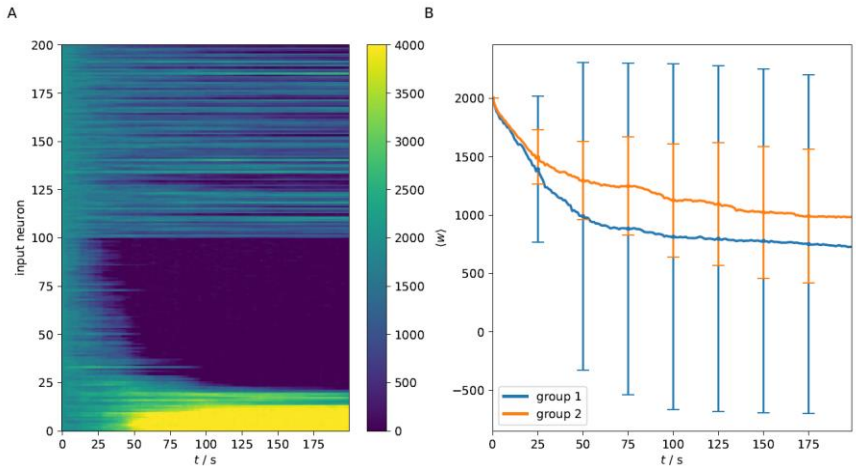

Figure 3.9

And the spikes look like Figure 4.1

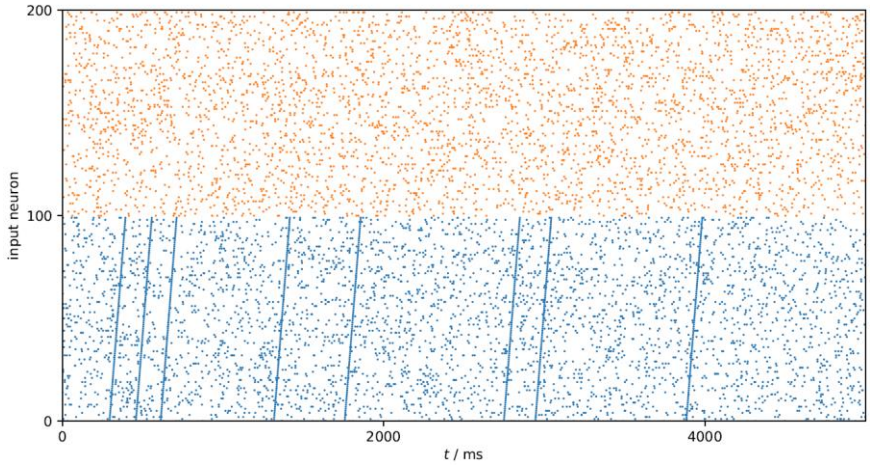

Figure 4.1

Task 4e

In this task, as per the model details, all neurons generate spikes according to Poisson processes with a constant rate $r_{background}$ = 8Hz. And Neurons in the first group additional fire in an organized fashion i.e all neurons in the group will fire at the same time when event occurs (Poisson processes with a constant rate r_{event} = 2Hz) . But this time sequence = False, jitter= 50ms and most importantly α = 0 which very clearly conveys that $-\lambda\alpha w^{\mu-}e^{-\frac{|\Delta t|}{\tau-}}$ if Δt < 0 from (1) gets 0 always in the sense, the synaptic weights never gets LTD. Which clearly informs the synaptic weights keep increasing as the spike trains are arriving towards every presynaptic terminal.
At region Δt < 0 since the spike fires from every neurons of group 1 would actually get along with at present synaptic efficacy and leads to play a dominant role in Synaptic weight changes compared to group 2. At region Δt >= 0 it is anyways by principle is the cause to LTP. But the contribution towards the synaptic changes from Group 1 to Group 2 varies slightly i.e

Group 2 synapses learn significantly quicker than Group 1 because of the absence of Jitter. Whereas, in Group 1 because of the presence of Jitter = 50ms it tries to disturb the dynamics of weight changes but still since the frequency of Group 1 neurons are pretty great it does not make a bigger impact in learning process. Henceforth from the Fig 4.3 it can be observed that Group 1 learns at slighter margin quicker than Group 2. In the absence of Jitter, it can have learnt even quicker.

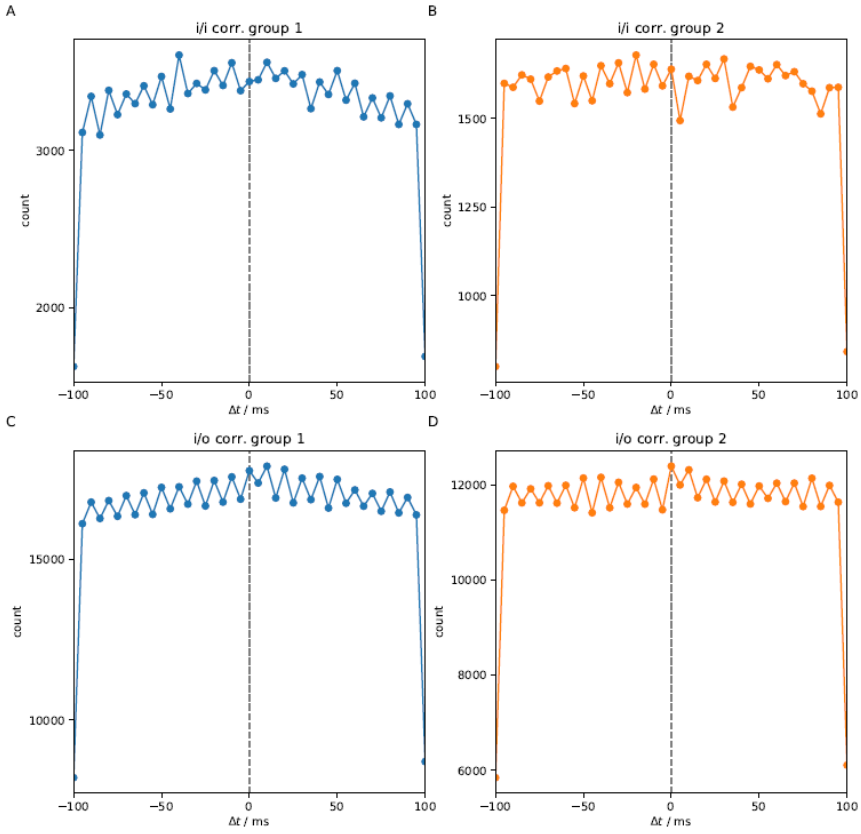

Figure 4.2

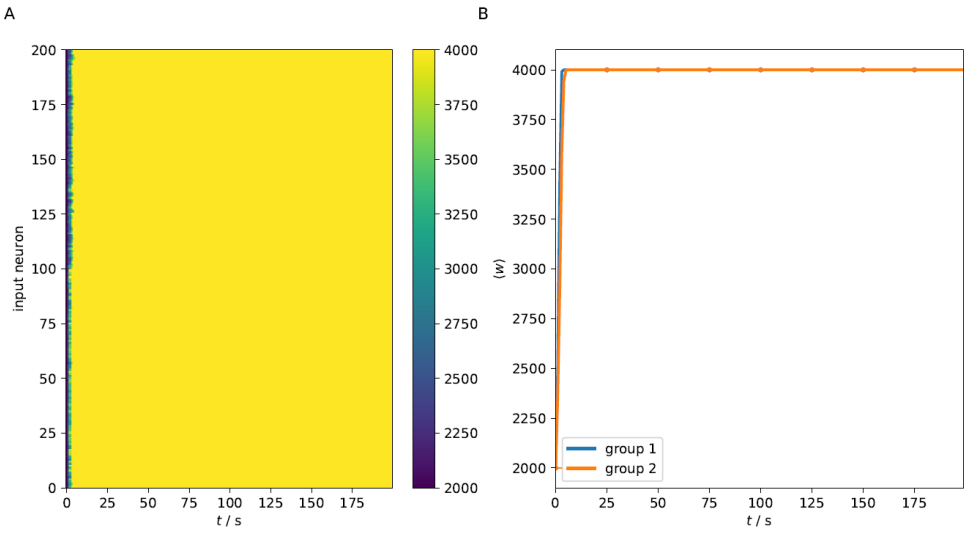

Figure 4.3

And the spikes look like Figure 4.4

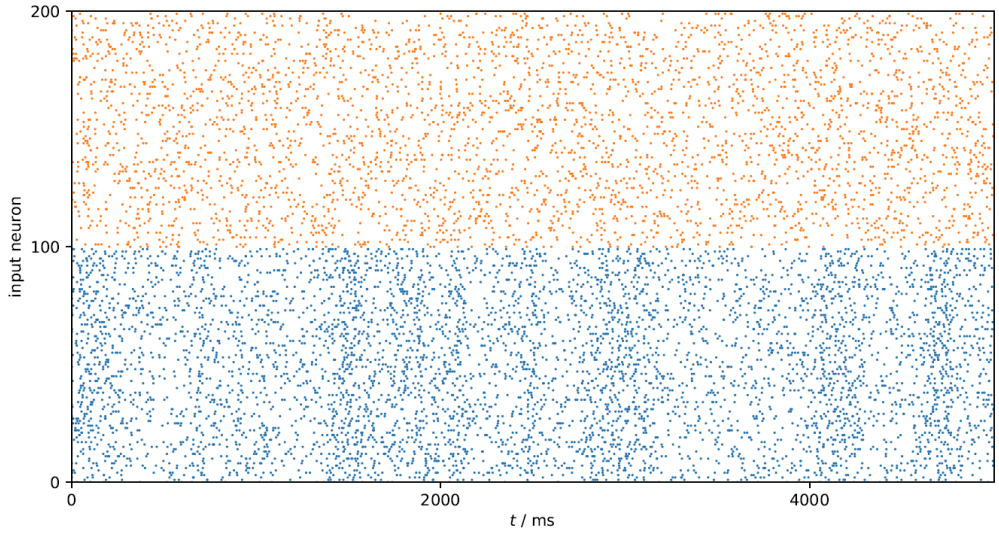

Figure 4.4