Incorporating temporal spike stability into the Forward-Forward algorithm

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1. Introduction

- **Spiking Neural Networks (SNNs)** are neural networks inspired by biological neurons and can be described by two main behaviors :
  - They use spikes to communicate
  - They integrate their input spikes and fire at a specific threshold
- This makes SNNs biologically plausible, but difficult and expensive to train using standard backpropagation as spike events are non-differentiable [1].
- The **Forward-Forward (FF) algorithm** [2] is an alternative to backpropagation that trains each layer locally using two passes:
  - A **positive pass** with correct input-label pairs
  - A **negative pass** with incorrect input-label pairs
- FF's objective is to assign higher **goodness** score to positive samples and lower **goodness** to negative samples.

Forward-Forward goodness gap

$$G_\Delta = G(h^{pos}) - G(h^{neg})$$

Standard goodness function

$$G(h) = \frac{1}{N}\sum_{i=1}^{N} C(h_i)^2$$

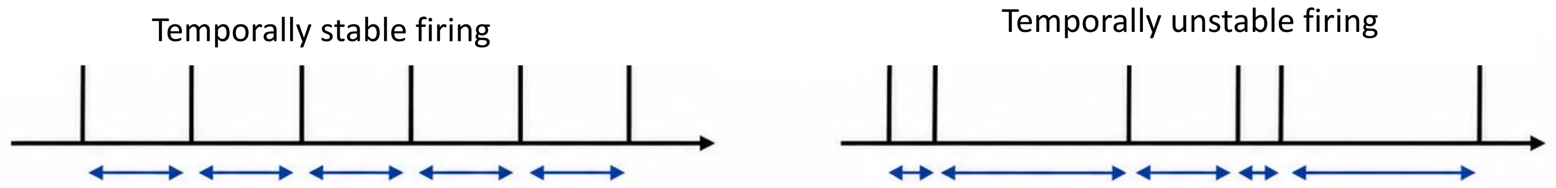
- **Problem**:
  Current FF-SNN methods only use aggregate spike-count activity as the goodness score [3], and ignore the inherent temporal properties of SNNs
- **Goal**:
  We investigate whether temporal stability in neuron spiking can provide useful information for the FF training of SNNs.

2. ISI-CV

- **Inter-Spike Interval Coefficient of Variation** (ISI-CV) is used to measure the temporal stability.
- It is used in both neuroscience [4] and computer science [5].

$$CV_{ISI} = \frac{\sigma(ISI)}{\mu(ISI)}$$

- At neuron level:
  - ISI is the time gap between two consecutive spikes.
  - ISI-CV is the variance between consecutive time gaps.
- **What does this mean ?**



3. Research Questions

The main research question is broken into multiple sub-questions that are each tested in a series of experiments. **Can temporal spike stability, measured using ISI-CV, improve Forward-Forward learning in Spiking Neural Networks?**

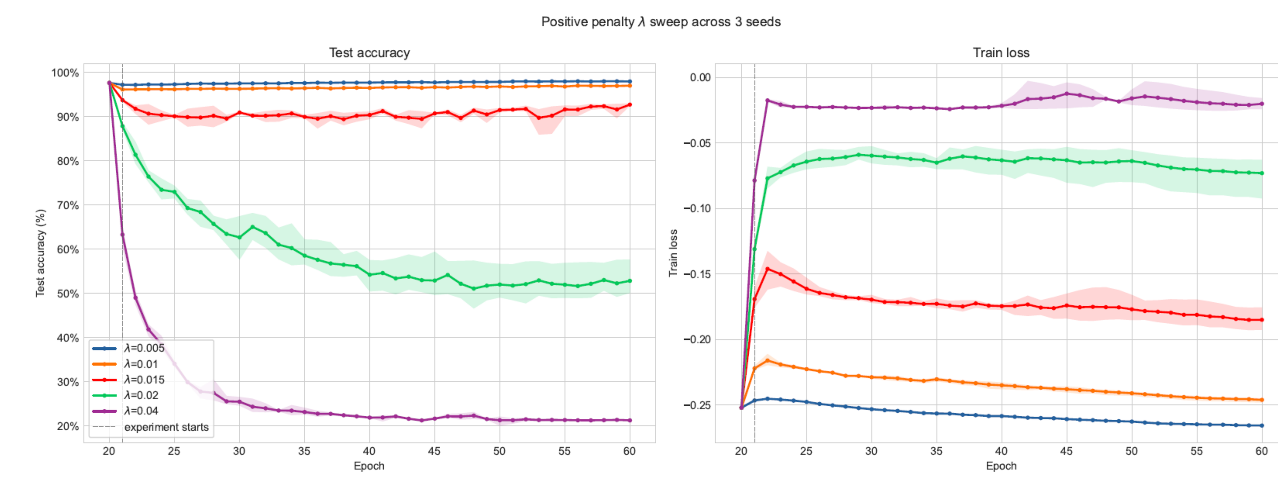
- Does direct ISI-CV optimization improve FF-SNN learning?
  Check: add an ISI-CV term to objective during training.
- Can ISI-CV identify stable neurons that should be protected during training?
  Check: use ISI-CV to select neurons to protect during training.
- Do FF trained SNNs already contain temporal stability information useful for classification, and can ISI-CV extract it ?
  Check: apply candidate scoring based on ISI-CV at classification.

4. Methods & Results

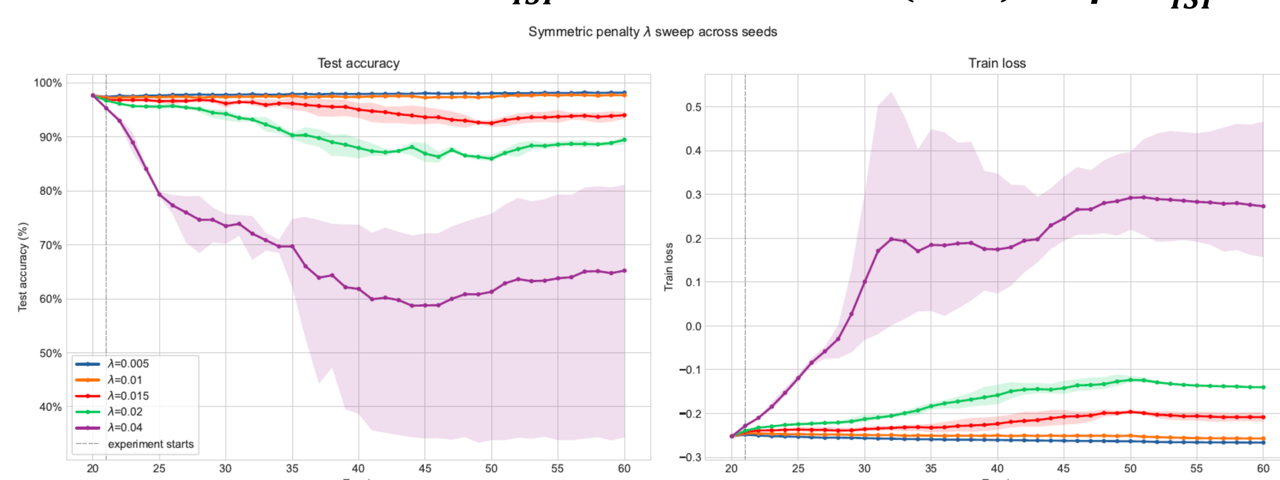
(1) Direct optimization

We test 3 methods of incorporating ISI-CV into the FF's objective. First 2 modify the goodness function, while the third adds a new separate objective to loss computation.

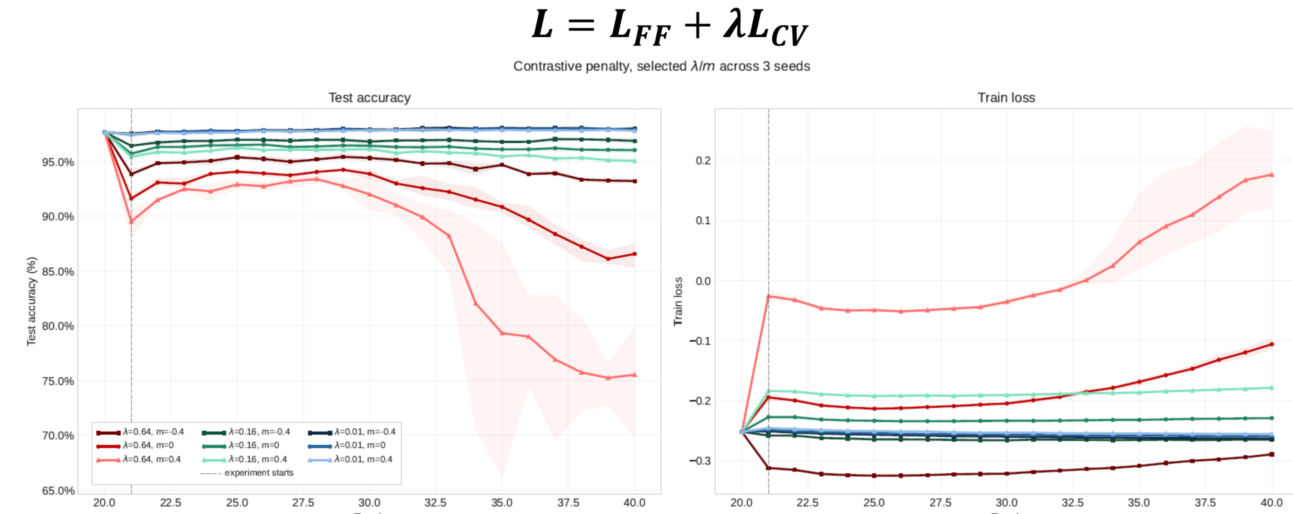
$$\widetilde{G^{pos}} = G(h^{pos}) - \lambda\rho CV_{ISI}^{pos}$$



$$\widetilde{G^{pos}} = G(h^{pos}) - \lambda\rho CV_{ISI}^{pos} \qquad \widetilde{G^{neg}} = G(h^{neg}) - \lambda\rho CV_{ISI}^{neg}$$



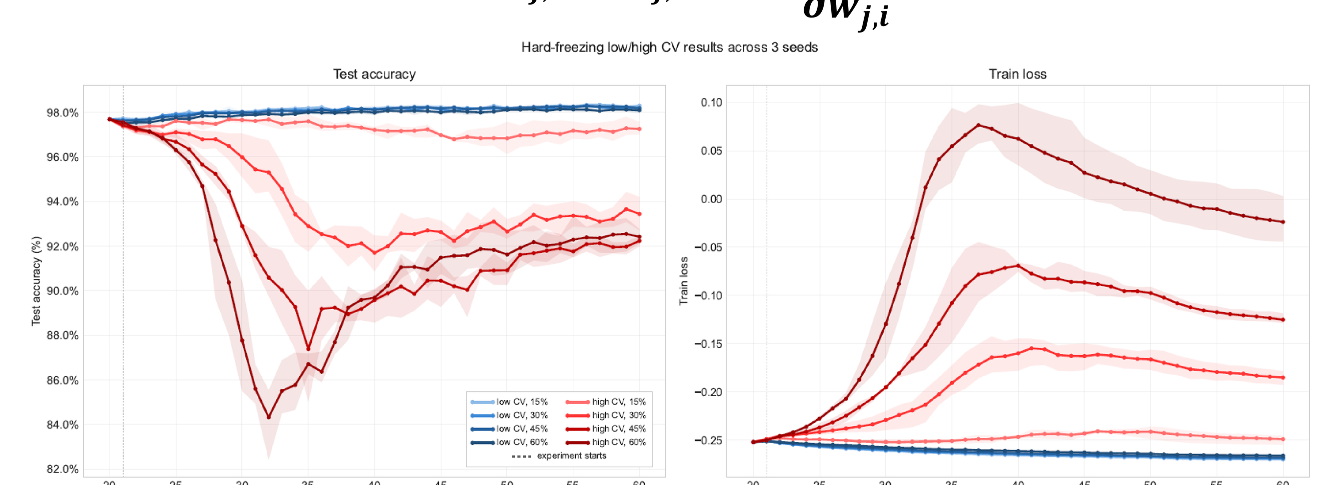
$$L = L_{FF} + \lambda L_{CV}$$



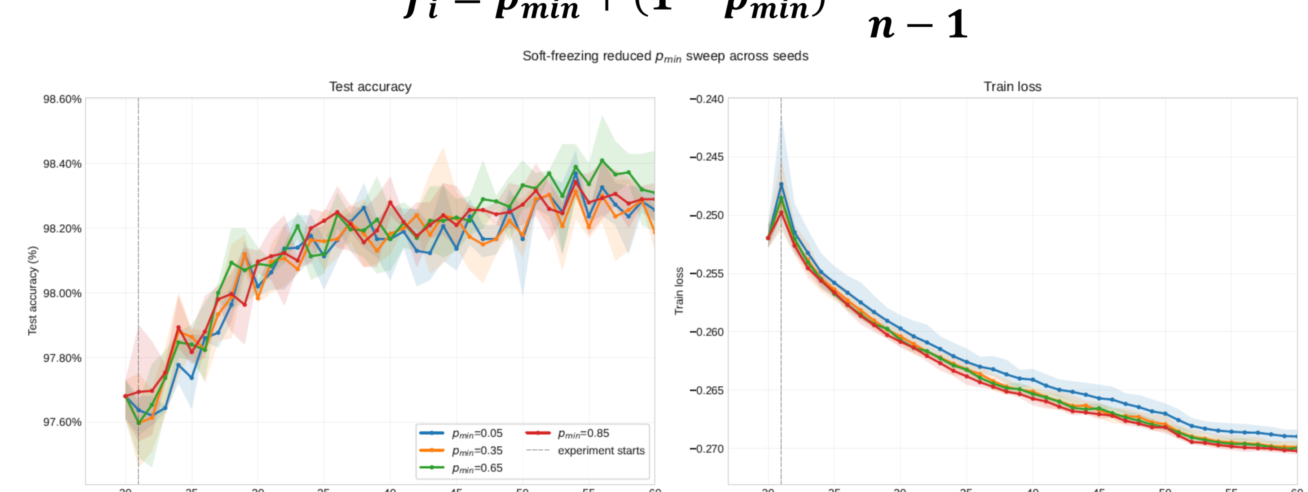
(2) Neuron protection

We test 2 methods of neuron protection mechanisms based on ISI-CV. First one fully freezes a subset of neurons, while the second one uses an ISI-CV based ranking to apply a soft freezing factor.

$$w_{j,i} \leftarrow w_{j,i} - \eta z_i \frac{\partial L}{\partial w_{j,i}}$$



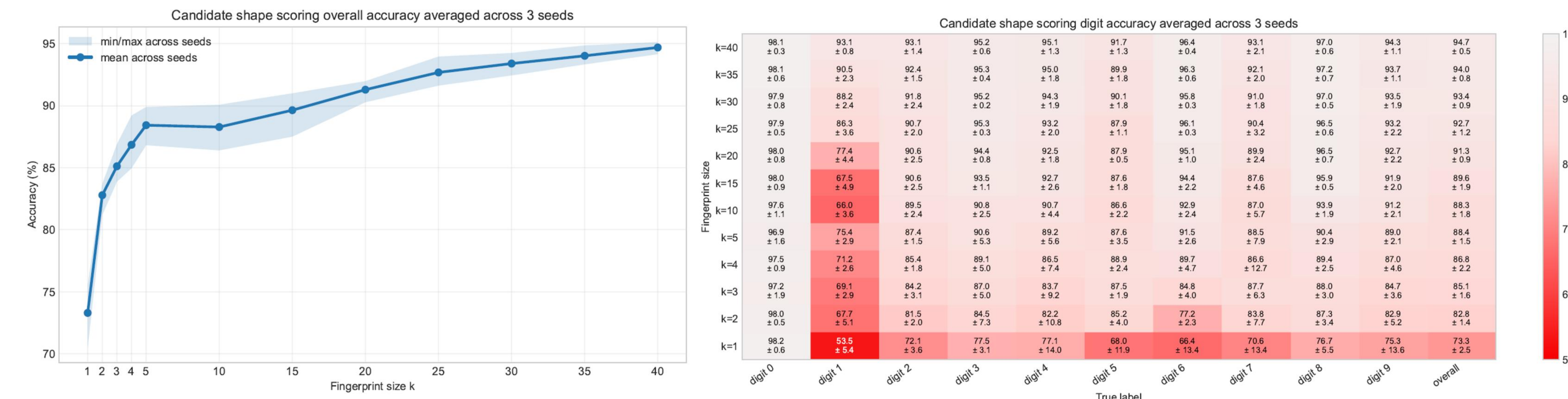
$$f_i = p_{min} + (1 - p_{min})\frac{\text{rank}(v_i)}{n-1}$$



(3) Candidate scoring

We test a method where class-specific temporal fingerprints are built from the most stable neurons and are used to create a candidate score for each label.

$$F_q = BottomK(CV_{ISI}) \qquad cs(x,q) = \frac{1}{K}\sum_{n\in F_q} CV_{ISI,n}^{(x,q)}$$



5. Conclusions

- **Direct ISI-CV optimization does not reliably improve FF-SNN learning.** Adding ISI-CV directly to the training objective conflicts with the Forward-Forward goodness objective and destabilizes training.
- **ISI-CV is useful as a plasticity-control signal.** Protecting temporally stable neurons during training improves or preserves accuracy, suggesting that low-ISI-CV neurons contain important learned representations.
- **FF-trained SNNs already contain class-specific temporal stability information.** ISI-CV-based candidate scoring performs well above chance, showing that spike timing contains useful information.
- **Overall, temporal spike stability can help Forward-Forward SNNs but not as a direct objective.** ISI-CV is most useful for identifying stable neurons and extracting temporal structure from already trained networks.

6. Future Work

- Test ISI-CV and alternatives on spike-based datasets, with richer temporal dynamics.
- Evaluate how much ISI-CV plasticity helps in the training process and evaluate it on larger SNN architectures and datasets.
- Evaluate how neuron parameters and input encoding affect temporal stability.
- Develop direct methods that use temporal stability without destabilizing FF training.

7. References

[1] Rongguang Ye, Chenhao Ye, Chao Huang, Ming Tang, and Yunhao Liu. Beyond-backpropagation training: Methods, applications, and perspectives. TechRxiv, 2026(0103), 2026. doi: 10.36227/techrxiv.176740426.63642005/v1. URL https://www.techrxiv.org/doi/abs/10.36227/techrxiv.176740426.63642005/v1.
[2] Geoffrey Hinton. The forward-forward algorithm: Some preliminary investigations, 2022. URL https://arxiv. org/abs/2212.13345.
[3] Mohammadnavid Ghader, Saeed Reza Kheradpisheh, Bahar Farahani, and Mahmood Fazlali. Backpropagation-free spiking neural networks with the forward-forward algorithm, 2025. URL https://arxiv.org/abs/2502.20411.
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Gen AI was used to design the drawing from ISI-CV chapter.