

E. Paxon Frady, Ph.D.

Intel, Neuromorphic Computing Lab
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Education

UC San Diego

Ph.D., Neuroscience specialization in Computational Neuroscience

2008–2014

La Jolla, CA

Thesis: *Scalable semi-supervised cell identification reveals canonical swim and preparatory networks.*

Advisors: William Kristan, Gert Cauwenberghs, Massimo Scanziani, Terry Sejnowski, Tim Gentner

California Institute of Technology

B.S., Computation and Neural Systems, Business Economics and Management

2004–2008

Pasadena, CA

Research Experience

Intel, Neuromorphic Computing Lab

Neuromorphic Algorithms Research Lead

Developed algorithms for spiking neuromorphic computing hardware.

2019–Pres

Santa Clara, CA

Redwood Center for Theoretical Neuroscience, UC Berkeley

Postdoctoral Scientist

Studied connectionist neural networks, linking algorithms to observations in neuroscience.

2016–2021

Berkeley, CA

Inscopix

Postdoctoral Scientist

Analyzed large-scale calcium imaging data.

2015

Palo Alto, CA

Numenta/UC Berkeley

Postdoctoral Scientist

Developed computational models of the cortex.

2015

San Francisco, CA

Microsoft Research

Intern with Eric Horvitz

Developed computational algorithms to analyze large-scale VSD imaging data.

2010

Redmond, WA

Eye-Predict

Software Engineer

Applied computational model of visual attention to advertising, product placement, and website layout optimization.

2007–2009

Los Angeles, CA

Teaching Experience

Neu 299: Introduction to vector symbolic architectures

Lecturer

Organized and lectured new course on modern VSA methods.

2021

Berkeley, CA

Neu 299: The art of modeling

Project Mentor

Worked with student in designing modeling projects to better understand experimental neuroscience data.

2021

Berkeley, CA

VS 265: Neural Computation

Guest Lecturer

Taught introduction to connectionist theory and computation with high-dimensional vectors.

2016, 2018

Berkeley, CA

Analytical Methods in Computational Neuroscience

Student Faculty

Involved in creating a student-run course on computational methods in neuroscience.

- Dimensionality reduction, principal components analysis, independent components analysis.

2012–2014

La Jolla, CA

Neural Systems & Behavior

Teaching Faculty

Taught fundamentals VSD Imaging in the leech and computational imaging analysis techniques.

2013–2014

Woods Hole, MA

UCSD Neurosciences Bootcamp

Teaching Assistant

Taught incoming Neuroscience graduate students fundamentals of electrophysiology and neuroscience in intensive two-week course.

- Intracellular recordings: action-potentials, synaptic potentials, and gap-junctions.
- Basics of dynamical systems: systems of differential equations, phase-planes, bifurcations, stability.

2009–2013

La Jolla, CA

Bootcamp Computational Special Project

Head TA

2009–2012

La Jolla, CA

Taught basic introduction to computational modeling in neuroscience covering a wide array of projects.

- o Matlab/python simulations: Hodgkin-Huxley, Izhikevich, Morris-Lecar models of action-potential, Calcium channel kinetics in vesicles, sub-cellular dendritic integration (NEURON), gain control in spiking neurons (Brian simulator), multi-stable pattern generating networks.

Physics 173/BGGN 266: Modern Physics/Biophysics Laboratory

Teaching Assistant

Lead students through electrophysiology project on leeches.

2010

La Jolla, CA

Awards, Grants & Fellowships

2023 Bell-labs Prize (finalist): Next-generation computing leveraging brain rhythms, dendrites and spikes.

2022 NSF: Algorithms for life-long learning.

2019 DARPA: Computing in superposition with high-dimensional vectors.

2018 NIH BRAIN Initiative: Building analysis tools and a theory framework for inferring principles of neural computation from multi-scale organization in brain recordings.

2018 Intel Neuromorphic Research Community: A structured approach to design algorithms for Loihi.

2018 Berkeley Deep Drive: Connectionist representations of compositional structure for sensor integration and situational awareness in autonomous vehicles.

2011–2012 INC Cognitive Neuroscience Fellowship: Development and validation of functional connectivity algorithms to understand recurrent neuronal circuitry and its relationship to behavior and cognition.

2009–2011 UCSD Interfaces Fellowship: Inferring homologous cells across animals to analyze neural circuits.

2007 Frank W. Wood SURF Fellow: Understanding the visual saliency of faces and text.

2006 Summer Undergraduate Research Fellowship: The relation between phase-noise and overt attention.

Publications

Peer-Reviewed Articles

1. Kleyko, D., Kymn, C.J., Thomas, A., Olshausen, B. A., Sommer, F.T., Frady, E. P. (2025). Principled neuromorphic reservoir computing. *Nature Communications* 16(1): 640.
2. Kymn, C., Mazelet, S., Thomas, A., Kleyko, D., Frady, E., Sommer, F., Olshausen, B. (2024). Binding in hippocampal-entorhinal circuits enables compositionality in cognitive maps. *Advances in neural information processing systems* 37: 39128-39157.
3. Kymn, C. J., Kleyko, D., Frady, E. P., Bybee, C., Kanerva, P., Sommer, F. T., Olshausen, B. A. (2024). Computing with residue numbers in high-dimensional representation. *Neural Computation* 37(1): 1-37.
4. Renner, A., Supic, L., Danieleescu, A., Indiveri, G., Olshausen, B.A., Sandamirskaya, Y., Sommer, F.T., Frady, E.P. (2024). Neuromorphic Visual Scene Understanding with Resonator Networks. *Nature Machine Intelligence* 6: 641-652.
5. Renner, A., Supic, L., Danieleescu, A., Indiveri, G., Frady, E.P., Sommer, F.T., Sandamirskaya, Y. (2024). Neuromorphic visual odometry with resonator networks. *Nature Machine Intelligence* 6: 653–663.
6. Kleyko, D., Rosato, A., Frady, E.P., Panella, M. and Sommer, F.T. (2023) Perceptron Theory Can Predict the Accuracy of Neural Networks. *IEEE Transactions on Neural Networks and Learning Systems* 1-15. doi: 10.1109/TNNLS.2023.3237381.
7. Kleyko, D., Bybee, C., Huang, P-C, Kymn, C.J., Olshausen, B.A., Frady, E.P., Sommer, F.T. (2023) Efficient Decoding of Compositional Structure in Holistic Representations. *Neural Computation* 35 (7): 1159–1186.
8. Kleyko, D., Davies, M., Frady, E.P., Kanerva, P., Kent, S.J., Olshausen, B.A., Osipov, E., Rabaey, J.M., Rachkovskij, D.A., Rahimi, A., Sommer, F.T. (2022) Vector Symbolic Architectures as a Computing Framework for Emerging Hardware. *Proceedings of the IEEE* 110 (10): 1538-1571.
9. Frady, E.P., Sanborn, S., Srestha, S., Ben-Dayan Rubin, D., Orchard, G., Sommer, F., Davies, M. (2022). Efficient neuromorphic signal processing with resonator neurons. *Journal of Signal Processing Systems* 94: 917-927.
10. Kleyko, D., Bybee, C., Khosrowshahi, A., Nikonov, D.E., Sommer, F.T., Frady, E.P. (2022). Integer factorization with compositional distributed representations. *Proceedings of the Neuro-Inspired Computational Elements Workshop*: 73-80.
11. Frady, E. P., Kleyko, D., Kymn, C. J., Olshausen, B. A., Sommer, F. T. (2022). Computing on functions using randomized vector representations (in brief). *Proceedings of the Neuro-Inspired Computational Elements Workshop*: 115-122.
12. Kleyko, D., Frady, E.P., Sommer, F.T. (2021). Cellular automata can reduce memory requirements of collective-state computing. *IEEE Transactions on Neural Networks and Learning Systems* 33(6): 2701-2713.
13. Frady, E.P., Kleyko, D., Sommer, F. (2021). Variable binding for sparse distributed representations: theory and applications. *IEEE Transactions on Neural Networks and Learning Systems* 34(5):2191-2204.
14. Kleyko, D., Frady, E.P., Kheffache, M., Osipov, E. (2020b). Integer Echo State Networks: Efficient Reservoir Computing for Digital Hardware. *IEEE Transactions on Neural Networks and Learning Systems* 33(4): 1688-1701.
15. Frady, E.P., Kent, S., Olshausen, B.A., Sommer, F.T. (2020). Resonator Networks, 1: An Efficient Solution for Factoring High-Dimensional, Distributed Representations of Data Structures. *Neural Computation* 32(12): 2311-2331.
16. Kent, S., Frady, E.P., Sommer, F.T., Olshausen, B.A. (2020). Resonator Networks, 2: Factorization Performance and

- Capacity Compared to Optimization-Based Methods. *Neural Computation* 32(12): 2332-2388.
17. Kleyko, D., Kheffache, M., Frady, E.P., Wiklund, U., Osipov, E. (2020). Density Encoding Enables Resource-Efficient Randomly Connected Neural Networks. *IEEE Transactions on Neural Networks and Learning Systems*.
 18. Frady, E. P., Orchard, G., Florey, D., Imam, N., Liu, R., Mishra, J., Tse, J., Wild, A., Sommer, F. T., Davies, M. (2020). Neuromorphic nearest neighbor search using Intel's Pohoiki Springs. *Proceedings of the Neuro-Inspired Computational Elements Workshop* 32(8): 3777-3783.
 19. Frady, E.P. & Sommer, F.T. (2019). Robust computation with rhythmic spike patterns. *PNAS* 116(36): 18050-18059.
 20. Frady, E.P., Kleyko, D., Sommer, F.T. (2018). A theory of sequence indexing and working memory in recurrent neural networks. *Neural Computation* 30(6): 1449-1513.
 21. Rahimi, A., Datta, S., Kleyko, D., Frady, E.P., Olshausen, B.A., Kanerva, P., Rabaey, J.M. (2017) High-dimensional computing as a nanoscale paradigm. *IEEE Trans. on Circuits and Systems* 64(9): 2508-2521.
 22. Lippi, G., Fernandes, C.C., Ewell, L.A., Romoli, B., Curia, G., Frady, E.P., Jensen, A.B., Chaabane, M.M., Belal, C., Nathanson, J.L., Zoli, M., Leutgeb, J.K., Biagini, G., Yeo, G.Y., Berg, D.K. (2016) MicroRNA-101 Regulates Multiple Development Programs to Constrain Excitation in Adult Neural Networks. *Neuron* 92(6): 1337-1351.
 23. Frady, E.P., Kapoor, A., Horvitz, E., Kristan, W.B. (2016). Scalable semi-supervised functional neurocartography reveals canonical neurons in behavioral networks. *Neural Computation* 28(8): 1453-1497.
 24. Berdyeva, T. K., Frady, E. P., Nassi, J. J., Aluisio, L., Cherkas, Y., Otte, S., Wyatt, R., Dugovic, C., Ghosh, K.K., Schnitzer, M.J., Lovenberg, T., Bonaventure, P. (2016). Direct Imaging of Hippocampal Epileptiform Calcium Motifs Following Kainic Acid Administration in Freely Behaving Mice. *Frontiers in Neuroscience*, 10, 53.
 25. Woodford, C.R., Frady, E.P., Smith, R., Morey, B., Canzi, G., Araneda, R., Kristan, W.B., Kubiak, C.P., Miller, E.M., Tsien, R.Y. (2015). Improved PeT molecules for optically sensing voltage in neurons. *J. Am. Chem. Soc.* 137: 1817.
 26. Miller, E.W., Lin, J.Y., Frady, E.P., Steinbach, P.A., Kristan, W.B., Tsien, R.Y. (2012). Optically monitoring voltage in neurons by photo-induced electron transfer through molecular wires. *PNAS* 109(6): 2114-2119.
 27. Cerf, M.*, Frady, E.P.*, Koch, C. (2009). Faces and text attract gaze independent of task: Experimental Data and Computer Model. *Journal of Vision* 9(12): 1-15.
 28. Einhauser, W., Rutishauser, U., Frady, E.P., Nadler S., Konig, P., Koch, C. (2006). The relation of phase noise and luminance contrast to overt attention in complex visual stimuli. *Journal of Vision* 6: 1148-58.

Pre-prints, Views & Proceedings.....

1. Frady, E.P., Kent, S., Tran, Q., Kanerva, P., Olshausen, B.A., Sommer, F.T. (2023). Learning and generalization of compositional representations of visual scenes. arXiv:2303.13691
2. Renner, A., Supic, L., Danieleescu, A., Indiveri, G., Olshausen, B.A., Sandamirskaya, Y., Sommer, F.T., Frady, E.P. (2022). Neuromorphic Visual Scene Understanding with Resonator Networks. arXiv:2208.12880 [cs.CV]
3. Renner, A., Supic, L., Danieleescu, A., Indiveri, G., Frady, E.P., Sommer, F.T., Sandamirskaya, Y. (2022). Neuromorphic visual odometry with resonator networks. arXiv:2208.12880 [cs.CV]
4. Bybee, C., Frady, E.P., Sommer, F.T. (2022). Deep learning in spiking phasor neural networks. arXiv:2204.00507.
5. Frady, E.P., Kleyko, D., Kymn, C.J., Olshausen, B.A., Sommer, F.T. (2021). Computing on functions using randomized vector representations. arXiv:2109.03429 [cs.LG]
6. Kleyko, D., Davies, M., Frady, E.P., Kanerva, P., Kent, S.J., Olshausen, B.A., Osipov, E., Rabaey, J.M., Rachkovskij, D., Rahimi, A., Sommer, F.T. (2021). Vector Symbolic Architectures as a Computing Framework for Nanoscale Hardware. arXiv:2106.05268 [cs.AR]
7. Kleyko, D., Rosato, A., Frady, E.P., Panella, M., Sommer, F.T. (2020). Perceptron Theory for Predicting the Accuracy of Neural Networks. arXiv:2012.07881 [cs.LG]
8. Kleyko, D., Frady, E.P., Sommer, F.T. (2020). Cellular automata can reduce memory requirements of collective-state computing. arXiv:2010.03585 [cs.NE]
9. Frady, E.P., Kleyko, D., Sommer, F.T. (2020). Variable binding for sparse distributed representations: theory and applications. arXiv:2009.06734 [cs.NE]
10. Kleyko, D., Kheffache, M., Frady, E.P., Wiklund, U., Osipov, E. (2019). Density Encoding Enables Resource-Efficient Randomly Connected Neural Networks. arXiv:1909.09153 [cs.LG]
11. Kent, S., Frady, E.P., Sommer, F.T., Olshausen, B.A. (2019). Resonator circuits for factoring high-dimensional vectors. arXiv:1906.11684 [cs.NE]
12. Frady, E.P., Kanerva, P., Sommer, F.T. (2019). Robust computation with rhythmic spike patterns. arXiv:1901.07718 [cs.NE]
13. Kleyko, D., Frady, E.P., Osipov, E. (2018). Integer Echo-State Networks: Hyperdimensional Reservoir Computing. arXiv:1706.00280 [cs.NE]
14. Frady, E.P., Kleyko, D., Sommer, F.T. (2017). Theory of the superposition principle for randomized connectionist representations in neural networks. arXiv:1707.01429 [cs.NE]
15. Frady, E.P., Kristan, W.B. (2015). The Imaging Computational Microscope: A Matlab tool for automatic analysis and visualization of large-scale imaging data. arXiv:1502.07009 [q-bio.NC]
16. Kapoor, A., Frady, E.P., Jegelka, S., Kristan, W.B., Horvitz, E. (2015). Inferring and Learning from Neural Correspondences. arXiv:1501.05973 [q-bio.NC]

17. **Frady, E.P., Kristan, W.B.** (2013). Computation with Population Codes. In: Jaeger D., Jung R. (Ed.) *Encyclopedia of Computational Neuroscience*: Springer Reference (www.springerreference.com). Springer-Verlag Berlin Heidelberg.
18. **Frady, E.P., Palmer, C.R., Kristan, W.B.** (2012). Sexual Attraction: Sex-Specific Wiring of Neural Circuitry. *Current Biology* 22(22): R953-R956.
19. **Cerf, M., Frady, E.P., Koch, C.** (2008). Using semantic content as cues for better scanpath prediction. *ETRA* 143-146.

Conference Presentations.....

1. **Frady, E.P.** (2025). Storing data structures in synapses: combining vector symbolic architectures with tensor product representations. *Neuromonster* [oral].
2. **Frady, E.P.** (2023). Computing in superposition with classical waves and spikes. *Telluride workshop on Neuromorphic Computing* ([invited](#)).
3. **Renner, A., Sandamirskaya, Y., Sommer, F.T., Frady, E.P.** (2022). Sparse vector binding on spiking neuromorphic hardware using synaptic delays. *International Conference on Neuromorphic Systems*.
4. **Orchard, G., Frady, E.P., Ben-Dayan Rubin, D., Sanborn, S., Srestha, S., Sommer, F., Davies, M.** (2021). Efficient neuromorphic signal processing with Loihi 2. *IEEE 2021 International Workshop on Signal Processing Systems*.
5. **Frady, E.P.** (2021). Hyperdimensional computing with complex representations. *VSA Workshop* ([online](#)).
6. **Frady, E.P.** (2020). VSAs and Resonator Networks: Towards Cognitive Computing on Neuromorphic Hardware. *VSA Workshop* ([online](#)).
7. **Frady, E.P., Sommer, F.T.** (2019). Robustly encoding multiple variables on smooth manifolds in a spiking model of hippocampus. *Society for Neuroscience* (Chicago, USA).
8. **Frady, E.P., Davies, M., Sommer, F.T.** (2019). Robust computation with rhythmic spike patterns on neuromorphic hardware. *Joint Symposium for Neural Computation* (Los Angeles, USA).
9. **Frady, E.P., Kanerva, P., Sommer, F.T.** (2019). A framework for linking computation and rhythm-based timing patterns in neural firing. *Computational and Systems Neuroscience* (Lisbon, Portugal).
10. **Frady, E.P., Kent, S., Kanerva, P., Olshausen, B.A., Sommer, F.T.** (2018). Cognitive neural systems for disentangling compositions. *Cognitive Computing* (Hannover, Germany).
11. **Frady, E.P., Kanerva, P., Sommer, F.T.** (2018). A framework for linking computation and rhythm-based timing patterns in neural firing. *Cognitive Computing* (Hannover, Germany).
12. **Frady, E.P., Kanerva, P., Sommer, F.T.** (2018). Spike-timing computation with complex vectors: emergence of theta oscillations, place-fields and phase-precession in a model of hippocampus. *Society for Neuroscience* (San Diego, USA).
13. **Frady, E.P., Kanerva, P., Sommer, F.T.** (2018). A memory network model using spike phase-precession. *Asilomar Conference on Signals, Systems, and Computers* (Asilomar, USA). [oral]
14. **Frady, E.P., Kanerva, P., Sommer, F.T.** (2018). A framework for linking computations and rhythm-based timing patterns in neural firing, such as phase-precession in hippocampal place cells. *Cognitive Computational Neuroscience* (Philadelphia, USA). [oral]
15. **Frady, E.P., Kent, S., Tran, Q., Kanerva, P., Olshausen, B.A., Sommer, F.T.** (2018). Resonator circuits: a model for inferring compositional structure in distributed representations. *Computational and Systems Neuroscience* (Denver, USA).
16. **Kleyko, D., Frady, E.P., Osipov, E.** (2018). Echo state networks based on hyperdimensional computing. *Neural Inspired Computational Elements* (Hillsboro, USA).
17. **Frady, E.P., Kleyko, D., Kanerva, P., Sommer, F.T.** (2016). The channel capacity and scaling of distributed neural activity. *Society for Neuroscience* (San Diego, USA).
18. **Berdyeva, T.K., Frady, E.P., Aluisio, L., Otte, S., Wyatt, R.M., Dugovic, C., Shelton, J., Ghosh, K., Schnitzer, M.J., Lovenberg, T., Bonaventure, P.** (2015). Direct imaging of calcium pathology preceding kainic acid induced seizure activity in freely behaving mice. *Society for Neuroscience* (Chicago, USA).
19. **Gulati, S., Frady, E.P., Cao, V., Joshi, P., Otte, S.L.** (2015). Multilayer cortical imaging in freely behaving animals. *Society for Neuroscience* (Chicago, USA).
20. **Sturgill, J.F., Frady, E.P., Isaacson, J.** (2015). Addition by division: a recurrent circuit explains cortical odor response regulation by SOM cells. *Computational and Systems Neuroscience* (Salt Lake City, USA). [oral]
21. **Frady, E.P., Kristan, W.B.** (2014). Scalable semi-supervised framework for activity mapping the leech nervous system. *Computation and Systems Neuroscience* (Salt Lake City, USA).
22. **Frady, E.P., Yudice, J., Konanur, V., Todd, K.L., French, K.A., Kristan, W.B.** (2013). Shunting and inhibitory currents co-regulate DE-3's input-output function. *Society for Neuroscience* (San Diego, USA).
23. **Frady, E.P., Yudice, J., Kristan, W.B.** (2013). Gain-control via shunting inhibition in a spiking model of the leech local bend reflex. *Computational and Systems Neuroscience* (Salt Lake City, USA).
24. **Frady, E.P., Kristan, W.B.** (2012). Inferring Homologous Cells Across Animals to Analyze Neural Circuits. *Organization for Computational Neurosciences* (Atlanta, USA). [oral]
25. **Frady, E.P., Kapoor, A., Horvitz, E., Kristan, W.B.** (2011). Utilizing multi-functional neuronal responses during different behaviors to uniquely identify all neurons in the leech ganglion. *Society for Neuroscience* (Washington D.C., USA).
26. **Frady, E.P., Kapoor, A., Horvitz, E., Kristan, W.B.** (2011). Isomap analysis of neuronal populations during decision-making. *Computational and Systems Neuroscience* (Salt Lake City, USA).

27. **Frady, E.P., Cauwenberghs, G.** (2009). Using dopamine as a modulator for STDP for reinforcement learning applied to Tic-Tac-Toe in a temporal difference framework. Society for Neuroscience (San Diego, USA).
28. **Frady, E.P., Cauwenberghs, G.** (2009). Multi-compartmental model of synaptic plasticity. Joint Symposium for Neural Computation (Los Angeles, USA).
29. **Cerf, M., Frady, E.P., Koch, C.** (2008). Subjects' inability to avoid looking at faces suggests bottom-up attention allocation mechanism for faces. Society for Neuroscience (Washington D.C., USA).