# E. Paxon Frady, Ph.D.

Intel, Neuromorphic Computing Lab
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## Education

**UC San Diego** **2008–2014**
*Ph.D., Neuroscience specialization in Computational Neuroscience* *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** **2004–2008**
*B.S., Computation and Neural Systems, Business Economics and Management* *Pasadena, CA*

## Research Experience

**Intel, Neuromorphic Computing Lab** **2019-Pres**
*Neuromorphic Algorithms Researcher* *Santa Clara, CA*
Developed algorithms for spiking neuromorphic computing hardware.

**Redwood Center for Theoretical Neuroscience, UC Berkeley** **2016–2021**
*Postdoctoral Scientist* *Berkeley, CA*
Studied connectionist neural networks, linking algorithms to observations in neuroscience.

**Inscopix** **2015**
*Postdoctoral Scientist* *Palo Alto, CA*
Analyzed large-scale calcium imaging data.

**Numenta/UC Berkeley** **2015**
*Postdoctoral Scientist* *San Francisco, CA*
Developed computational models of the cortex.

**Microsoft Research** **2010**
*Intern with Eric Horvitz* *Redmond, WA*
Developed computational algorithms to analyze large-scale VSD imaging data.

**Eye-Predict** **2007–2009**
*Software Engineer* *Los Angeles, CA*
Applied computational model of visual attention to advertising, product placement, and website layout optimization.

## Teaching Experience

**Neu 299: Introduction to vector symbolic architectures** **2021**
*Lecturer* *Berkeley, CA*
Organized and lectured new course on modern VSA methods.

**Neu 299: The art of modeling** **2021**
*Project Mentor* *Berkeley, CA*
Worked with student in designing modeling projects to better understand experimental neuroscience data.

**VS 265: Neural Computation** **2016,2018**
*Guest Lecturer* *Berkeley, CA*
Taught introduction to connectionist theory and computation with high-dimensional vectors.

**Analytical Methods in Computational Neuroscience** **2012–2014**
*Student Faculty* *La Jolla, CA*
Involved in creating a student-run course on computational methods in neuroscience.
- Dimensionality reduction, principal components analysis, independent components analysis.

**Neural Systems & Behavior** **2013–2014**
*Teaching Faculty* *Woods Hole, MA*
Taught fundamentals VSD Imaging in the leech and computational imaging analysis techniques.

**UCSD Neurosciences Bootcamp** **2009–2013**
*Teaching Assistant* *La Jolla, CA*
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.

**Bootcamp Computational Special Project** **2009–2012**
*Head TA* *La Jolla, CA*

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

- 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** **2010**
*Teaching Assistant* *La Jolla, CA*
Lead students through electrophysiology project on leeches.

# Grants & Fellowships

**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. **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 Procesing Systems.*
2. **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*.
3. **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*.
4. **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.
5. **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.
6. **Kleyko, D., Kheffache, M., Frady, E.P., Wiklund, U., Osipov, E.** (2020a). Density Encoding Enables Resource-Efficient Randomly Connected Neural Networks. *IEEE Transactions on Neural Networks and Learning Systems*.
7. **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. In *Proceedings of the Neuro-Inspired Computational Elements Workshop*, NICE '20, New York, NY, USA. Association for Computing Machinery.
8. **Frady, E.P. & Sommer, F.T.** (2019). Robust computation with rhythmic spike patterns. *PNAS* 116(36): 18050-18059.
9. **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.
10. **Rahimi, A., Datta, S., Kleyko, D., Frady, E.P., Olshausen, B.A., Kanerva, P., Rabaey, J.M.** (2017) High-dimensional computing as a nanoscalable paradigm. *IEEE Trans. on Circuits and Systems* 64(9): 2508-2521.
11. **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.
12. **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.
13. **Berdyyeva, 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.
14. **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.
15. **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.
16. **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.
17. **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., Kleyko, D., Kymn, C.J., Olshausen, B.A., Sommer, F.T.** (2021). Computing on functions using randomized vector representations. arXiv:2109.03429 [cs.LG]
2. **Kleyko, D., Davies, M., Frady, E.P., Kanerva, P., Kent, S.J., Olshuasen, 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]
3. **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]
4. **Kleyko, D., Frady, E.P., Sommer, F.T.** (2020). Cellular automata can reduce memory requirements of collective-state computing. arXiv:2010.03585 [cs.NE]
5. **Frady, E.P., Kleyko, D., Sommer, F.T.** (2020). Variable binding for sparse distributed representations: theory and applications. arXiv:2009.06734 [cs.NE]
6. **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]
7. **Kent, S., Frady, E.P., Sommer, F.T., Olshausen, B.A.** (2019). Resonator circuits for factoring high-dimensional vectors. arXiv:1906.11684 [cs.NE]
8. **Frady, E.P., Kanerva, P., Sommer, F.T.** (2019). Robust computation with rhythmic spike patterns. arXiv:1901.07718 [cs.NE]
9. **Kleyko, D., Frady, E.P., Osipov, E.** (2018). Integer Echo-State Networks: Hyperdimensional Reservoir Computing. arXiv:1706.00280 [cs.NE]
10. **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]
11. **Frady, E.P., Kristan, W.B.** (2015). The Imaging Computational Microscope: A Matlab tool for automatic anlaysis and visualization of large-scale imaging data. arXiv:1502.07009 [q-bio.NC]
12. **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]
13. **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.
14. **Frady, E.P., Palmer, C.R., Kristan, W.B.** (2012). Sexual Attraction: Sex-Specific Wiring of Neural Circuitry. Current Biology 22(22): R953-R956.
15. **Cerf, M., Frady, E.P., Koch, C.** (2008). Using semantic content as cues for better scanpath prediction. ETRA 143-146.
16. **Frady, E.P., Kleyko, D., Trann, Q., Kanerva, P.** (in prep.). On inverting compound representations of English verbs.
17. **Frady, E.P., Yudice, J., Konanur, V., Todd, K.L., French, K.A., Kristan, W.B.** (in prep.). Shunting and inhibitory currents co-regulate the input-output function of an identified leech neuron.
18. **Bybee, C., Frady, E.P., Sommer, F.T.** (in prep). Deep learning in spiking phasor neural networks.

## Conference Presentations

1. **Frady, E.P.** (2021). Hyperdimensional computing with complex representations. VSA Workshop (online).
2. **Frady, E.P.** (2020). VSAs and Resonator Networks: Towards Cognitive Computing on Neuromorphic Hardware. VSA Workshop (online).
3. **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).
4. **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).
5. **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).
6. **Frady, E.P., Kent, S., Kanerva, P., Olshausen, B.A., Sommer, F.T.** (2018). Cognitive neural systems for disentangling compositions. Cognitive Computing (Hannover, Germany).
7. **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).
8. **Frady, E.P., Kanerva, P., Sommer, F.T.** (2018). Spike-timing computation with complex vectors: emergence of theta oscillations, place-fields and phase-precssion in a model of hippocampus. Society for Neuroscience (San Diego, USA).
9. **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]**
10. **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]**
11. **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).
12. **Kleyko, D., Frady, E.P., Osipov, E.** (2018). Echo state networks based on hyperdimensional computing. Neural Inspired Computational Elements (Hillsboro, USA).

13. **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).
14. **Berdyyeva, 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).
15. **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).
16. **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]**
17. **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).
18. **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).
19. **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).
20. **Frady, E.P., Kristan, W.B.** (2012). Inferring Homologous Cells Across Animals to Analyze Neural Circuits. Organization for Computational Neurosciences (Atlanta, USA). **[oral]**
21. **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).
22. **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).
23. **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).
24. **Frady, E.P., Cauwenberghs, G.** (2009). Multi-compartmental model of synaptic plasticity. Joint Symposium for Neural Computation (Los Angeles, USA).
25. **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).