

Example projects

- Studying accuracy and robustness of models using frames (conventions) vs. equivariance vs. traditional (non-equivariant)
- Using learning objectives in 6.S966 to apply to other [algebraic structures](#) or projections
- ...

Disclaimer: there are tons of papers in this area -- this is not an exhaustive list!

See also <https://github.com/Chen-Cai-OSU/awesome-equivariant-network>

Recent papers are at the cutting edge; papers released a few years ago are more foundational

Topics:

- Architectures
 - Convolutional networks (in general)
 - [Group Equivariant Convolutional Networks, 2016](#)
 - [On the Generalization of Equivariance and Convolution in Neural Networks to the Action of Compact Groups, 2018](#)
 - Steerable networks
 - [Steerable CNNs, 2016](#)
 - [3D Steerable CNNs: Learning Rotationally Equivariant Features in Volumetric Data, 2018](#)
 - [General E\(2\) - Equivariant Steerable CNNs, 2019](#)
 - Spherical data
 - [Spherical CNNs, 2018](#)
 - [Clebsch–Gordan Nets: a Fully Fourier Space Spherical Convolutional Neural Network, 2018](#)
 - Graphical data
 - [Provably Powerful Graph Networks, 2019](#)
 - [Understanding and Extending Subgraph GNNs by Rethinking Their Symmetries, 2022](#)
 - [Sign and Basis Invariant Networks for Spectral Graph Representation Learning, 2022](#)
 - [Complete Neural Networks for Euclidean Graphs, 2023](#)
 - Set data / other permutational symmetries
 - [Deep Sets, 2018](#)
 - [On Learning Sets of Symmetric Elements, 2020](#)
 - Point cloud and geometric graph data
 - [Tensor field networks: Rotation- and translation-equivariant neural networks for 3D point clouds, 2018](#)
 - [Vector Neurons: A General Framework for SO\(3\)-Equivariant Networks, 2021](#)
 - [SE\(3\)-Transformers: 3D Roto-Translation Equivariant Attention Networks, 2020](#)
 - [Geometric and Physical Quantities Improve E\(3\) Equivariant Message Passing, 2022](#)
 - Lie groups

- [Generalizing Convolutional Neural Networks for Equivariance to Lie Groups on Arbitrary Continuous Data, 2020](#)
 - [A General Theory of Equivariant CNNs on Homogeneous Spaces, 2020](#)
 - [A Practical Method for Constructing Equivariant Multilayer Perceptrons for Arbitrary Matrix Groups, 2021](#)
- Theoretical properties
 - Universality and function approximation
 - [Universal approximations of invariant maps by neural networks, 2018](#)
 - Graph neural networks
 - [On the Universality of Invariant Networks, 2019](#)
 - [Universal Invariant and Equivariant Graph Neural Networks, 2019](#)
 - [Scalars are universal: Equivariant machine learning, structured like classical physics, 2023](#)
 - [On the Universality of Rotation Equivariant Point Cloud Networks, 2020](#)
 - [Exponential Separations in Symmetric Neural Networks, 2022](#)
 - Sample complexity and generalization
 - [Provably Strict Generalisation Benefit for Equivariant Models, 2021](#)
 - [Learning with invariances in random features and kernel models, 2021](#)
 - [An Analysis of the Effect of Invariance on Generalization in Neural Networks, 2019](#)
 - [Understanding the Generalization Benefit of Model Invariance from a Data Perspective, 2021](#)
 - [On the Sample Complexity of Learning under Invariance and Geometric Stability, 2021](#)
 - [A PAC-Bayesian Generalization Bound for Equivariant Networks, 2022](#)
 - Optimization
 - [Implicit Bias of Linear Equivariant Networks, 2022](#)
 - [On the Implicit Bias of Linear Equivariant Steerable Networks: Margin, Generalization, and Their Equivalence to Data Augmentation, 2023](#)
- Approximate symmetries
 - [Residual Pathway Priors for Soft Equivariance Constraints, 2021](#)
 - [Approximately Equivariant Networks for Imperfectly Symmetric Dynamics, 2022](#)
 - [A General Theory of Correct, Incorrect, and Extrinsic Equivariance, 2023](#)
 - Breaking symmetries
 - [Finding symmetry breaking order parameters with Euclidean neural networks, 2021](#)
 - [Breaking the Symmetry: Resolving Symmetry Ambiguities in Equivariant Neural Networks, 2022](#)
 - [Discovering Symmetry Breaking in Physical Systems 2024](#)
 - [Symmetry Breaking Sets 2023](#)
- Learning symmetries
 - [Meta-Learning Symmetries by Reparameterization, 2021](#)
 - [Automatic Symmetry Discovery with Lie Algebra Convolutional Network, 2021](#)
 - [Learning Invariances in Neural Networks, 2020](#)
 - [Discovering Symmetry Group Structures via Implicit Orthogonality Bias 2024](#)

- Equivariant reinforcement learning
 - [SO\(2\) -Equivariant Reinforcement Learning, 2022](#)
 - [MDP Homomorphic Networks: Group Symmetries in Reinforcement Learning, 2020](#)
- Equivariant self-supervised learning
 - [Robust Self-Supervised Learning with Lie Groups, 2022](#)
 - [Equivariant Contrastive Learning, 2022](#)
- Equivariant generative models
 - [Equivariant Flows: Exact Likelihood Generative Learning for Symmetric Densities, 2020](#)
 - [E\(n\) Equivariant Normalizing Flows, 2022](#)
 - [Symphony: Symmetry-Equivariant Point-Centered Spherical Harmonics for Molecule Generation 2024](#)
 - [Ophiuchus: Scalable Modeling of Protein Structures through Hierarchical Coarse-graining SO\(3\)-Equivariant Autoencoders, 2023](#)
 - [MatterGen: a generative model for inorganic materials design 2023](#)
- Equivariant autoencoders
 - [Unsupervised Learning of Group Invariant and Equivariant Representations](#)
- Encoding symmetries in latent spaces
 - [Structuring Representations Using Group Invariants, 2022](#)
 - [Cross-Domain 3D Equivariant Image Embeddings, 2019](#)
 - [Learning Symmetric Embeddings for Equivariant World Models, 2022](#)
- Non-architectural approaches to equivariance
 - Data augmentation
 - [A Group-Theoretic Framework for Data Augmentation, 2019](#)
 - Frames
 - [Frame Averaging for Invariant and Equivariant Network Design, 2021](#)
 - Separators
 - [Low Dimensional Invariant Embeddings for Universal Geometric Learning, 2022](#)
 - [Group-invariant max filtering, 2022](#)
 - [Equivariance with Learned Canonicalization Functions, 2023](#)
- Symmetries in learning algorithms
 - [Why Are Convolutional Nets More Sample Efficient than Fully-Connected Nets?, 2021](#)
 - [On the non-universality of deep learning: quantifying the cost of symmetry, 2022](#)
- Symmetries of neural networks
 - [Equivariant Architectures for Learning in Deep Weight Spaces, 2023](#)
 - [Permutation Equivariant Neural Functionals, 2023](#)
- Gauge equivariance
 - [Gauge Equivariant Convolutional Networks and the Icosahedral CNN, 2019](#)
- Miscellaneous
 - [The Lie Derivative for Measuring Learned Equivariance, 2022](#)
- Applications (just a few samples -- this is by no means an exhaustive list!)
 - Drug discovery / biology

- [Equivariant Diffusion for Molecule Generation in 3D, 2022](#)
 - [DiffDock: Diffusion Steps, Twists, and Turns for Molecular Docking, 2023](#)
- Chemistry / materials / molecular dynamics
 - [Cormorant: Covariant Molecular Neural Networks, 2019](#)
 - [MACE: Higher Order Equivariant Message Passing Neural Networks for Fast and Accurate Force Fields, 2023](#)
 - [E\(3\)-Equivariant Graph Neural Networks for Data-Efficient and Accurate Interatomic Potentials, 2021](#)
 - [Equiformer: Equivariant Graph Attention Transformer for 3D Atomistic Graphs, 2023](#)
 - [Spherical Channels for Modeling Atomic Interactions, 2022](#)
 - [EquiformerV2: Improved Equivariant Transformer for Scaling to Higher-Degree Representations](#)
- PDEs and dynamics
 - [Incorporating Symmetry into Deep Dynamics Models for Improved Generalization, 2020](#)
 - [Lie Point Symmetry Data Augmentation for Neural PDE Solvers, 2022](#)
- Astronomy
 - [Translation and Rotation Equivariant Normalizing Flow \(TRENF\) for Optimal Cosmological Analysis, 2022](#)
- Physics
 - [Lorentz Group Equivariant Neural Network for Particle Physics, 2020](#)
 - [Equivariant Flow-Based Sampling for Lattice Gauge Theory, 2020](#)
- Robotics
 - [Edge Grasp Network: A Graph-Based SE\(3\)-invariant Approach to Grasp Detection, 2022](#)
- Vision
 - [Equivariant Multi-View Networks, 2019](#) (see also Kostas Daniilidis and Leonidas Guibas' labs' work more generally)