Geometry of Equivariant Linear Neural Networks

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Motivation

Two questions

1. How do the network’s properties affect the geometry of its function space? How to characterize equivariance or invariance?

2. How to parameterize equivariant and invariant networks? Which implications does it have for network design?
Training neural networks

Neural networks

A neural network $F$ of depth $L$ is a parameterized family of functions $(f_{L,\theta}, \ldots, f_{1,\theta})$

$$F: \mathbb{R}^N \rightarrow \mathcal{F}, \quad F(\theta) = f_{L,\theta} \circ \cdots \circ f_{1,\theta} =: f_{\theta}.$$ 

Each layer $f_{k,\theta}: \mathbb{R}^{d_{k-1}} \rightarrow \mathbb{R}^{d_k}$ is a composition activation $\circ$ (affine-)linear.

Training a network

Given training data $D = \{(\hat{x}_i, \hat{y}_i)_{i=1,\ldots,S}\} \subset \mathbb{R}^{d_0} \times \mathbb{R}^{d_L}$, the aim is to minimize the loss

$$\mathcal{L}: \mathbb{R}^N \xrightarrow{F} \mathcal{F} \xrightarrow{\ell_D} \mathbb{R}.$$ 

Example: For $\ell_D$ the squared error loss, this gives

$$\min_{\theta \in \mathbb{R}^N} \sum_{i=1}^S (f_{\theta}(\hat{x}_i) - \hat{y}_i)^2.$$ 

On function space: $\min_{M \in \mathcal{F}} \| M\hat{X} - \hat{Y} \|^2_{\text{Frob}}$.

Critical points of $\mathcal{L}$

- **pure**: critical point of $\ell_D$  
- **spurious**: induced by parameterization
Linear convolutional networks (LCNs)

- **linear**: identity as activation function
- **convolutional**: layers with filter $w \in \mathbb{R}^k$ and stride $s \in \mathbb{N}$:

$$\alpha_{w,s} : \mathbb{R}^d \to \mathbb{R}^{d'} , \quad (\alpha_{w,s}(x))_i = \sum_{j=0}^{k-1} w_j x_{is+j} .$$

### Geometry of linear convolutional networks [1]

Function space $\mathcal{F}_{(d,s)}$ of LCN: semi-algebraic set, Euclidean-closed

### Theorem [2]

Let $(d, s)$ be an LCN architecture with all strides $> 1$ and $N \geq 1 + \sum_i d_i s_i$. For almost all data $\mathcal{D} \in (\mathbb{R}^{d_0} \times \mathbb{R}^{d_L})^N$, every critical point $\theta_c$ of $\mathcal{L}$ satisfies one of the following:

1. $F(\theta_c) = 0$, or
2. $\theta_c$ is a regular point of $F$ and $F(\theta_c)$ is a **smooth, interior point** of $\mathcal{F}_{(d,s)}$.

In particular, $F(\theta_c)$ is a critical point of $\ell_\mathcal{D}_{\text{Reg}}(\mathcal{F}_{(d,s)}^0)$.

This is known to be false for...

- linear fully-connected networks
- stride-one LCNs

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Algebraic geometry for machine learning

Natural points of entry

◊ algebraic vision [3]  ◊ geometry of function spaces

Algebraic varieties

subsets of $\mathbb{C}^n$ obtained as common zero set of polynomials $p_1, \ldots, p_N \in \mathbb{C}[x_1, \ldots, x_n]$

Drawing real points of algebraic varieties

\[ \mathcal{V}(y^2 - x^2(x + 1)) \text{ a nodal curve} \]
\[ \mathcal{V}(x^2y - y^3 - z^3) \text{ a cubic surface} \]
\[ \mathcal{V}(p_0p_2 - (p_0 + p_1)p_1) \cap \Delta_2 \text{ a discrete statistical model} \]

Fully connected linear neural networks

Example

\( F : \mathbb{R}^{2 \times 4} \times \mathbb{R}^{3 \times 2} \rightarrow \mathbb{R}^{3 \times 4}, \ (M_1, M_2) \mapsto M_2 \cdot M_1 \)

parameter space: \( \mathbb{R}^N = \mathbb{R}^{2 \times 4} \times \mathbb{R}^{3 \times 2}, \ f_1, \theta = M_1, \ f_2, \theta = M_2 \)

Its function space \( \mathcal{F} \) is the set of real points of the determinantal variety

\[
\mathcal{M}_{2,3 \times 4}(\mathbb{R}) = \left\{ M \in \mathbb{R}^{3 \times 4} \mid \text{rank}(M) \leq 2 \right\}.
\]

The determinantal variety \( \mathcal{M}_{r,m \times n} \)

For \( M = (m_{ij})_{i,j} \in \mathbb{C}^{m \times n} : \ \text{rank}(M) \leq r \Leftrightarrow \) all \( (r + 1) \times (r + 1) \) minors of \( M \) vanish.

Define

\[
\mathcal{M}_{r,m \times n} = \{ M \mid \text{rank}(M) \leq r \} \subset \mathbb{C}^{m \times n}.
\]

Well studied! \( \text{dim}(\mathcal{M}_{r,m \times n}) = r \cdot (m + n - r), \ \mathcal{M}_{r,m \times n}(\mathbb{R}), \text{singularities, } \ldots \)
Invariant functions

\[ f_\theta : \mathbb{R}^n \to \mathbb{R}^r \to \mathbb{R}^m \quad r < \min(m, n) \]

\[ G = \langle \sigma_1, \ldots, \sigma_g \rangle \leq S_n \]

a permutation group, acting on \( \mathbb{R}^n \) by permuting the entries

induced action on \( M \): permuting its columns

Invariance under \( \sigma \in S_n \): \( f_\theta \circ \sigma \equiv f_\theta \)

Decomposing into cycles

The decomposition \( \sigma = \pi_1 \circ \cdots \circ \pi_k \) of \( \sigma \) into \( k \) disjoint cycles induces a partition

\[ \mathcal{P}(\sigma) = \{A_1, \ldots, A_k\} \]

of the set \( [n] = \{1, \ldots, n\} \). \( A_1, \ldots, A_k \subset [n] \) pairwise disjoint sets

Example: The permutation \( \sigma = (1 2 3 4 5) = (1 3 4)(2 5) \in S_5 \) induces the partition

\[ \mathcal{P}(\sigma) = \{\{1, 3, 4\}, \{2, 5\}\} \] of \([5] = \{1, 2, 3, 4, 5\} \). For \( \eta = (1 4 3)(2 5) \neq \sigma \): \( \mathcal{P}(\eta) = \mathcal{P}(\sigma) \).

Characterizing invariance \( \quad MP_\sigma \upharpoonright M \)

Let \( \sigma \in S_n \) and \( \mathcal{P}(\sigma) = \{A_1, \ldots, A_k\} \) its induced partition. A matrix \( M = (m_1 | \cdots | m_n) \) is invariant under \( \sigma = \pi_1 \circ \cdots \circ \pi_k \) if and only if for each \( i \), the columns \( \{m_j\}_{j \in A_i} \) coincide.

\[ \Rightarrow \] If \( M \) is invariant under \( \sigma \), its rank is at most \( k \).
Example: rotation-invariance for $p \times p$ pictures

**Setup:** $n = p^2$ an even square number, $f_\theta : \mathbb{R}^n \to \mathbb{R}^n$ linear

$\sigma \in S_n$: rotating a $p \times p$ picture clockwise by 90 degrees:

$$\sigma : \mathbb{R}^{p \times p} \to \mathbb{R}^{p \times p}, \quad \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1p} \\ a_{21} & a_{22} & \cdots & a_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ a_{p1} & a_{p2} & \cdots & a_{pp} \end{pmatrix} \mapsto \begin{pmatrix} a_{p1} & a_{p-1,1} & \cdots & a_{11} \\ a_{p2} & a_{p-1,2} & \cdots & a_{12} \\ \vdots & \vdots & \ddots & \vdots \\ a_{pp} & a_{p,p-1} & \cdots & a_{1p} \end{pmatrix}$$

Identify $\mathbb{R}^{p \times p} \cong \mathbb{R}^n$ via $A \mapsto (a_{1,1}, a_{1,p}, a_{p,p}, a_{p,1}, a_{1,2}, a_{2,p}, a_{p,p-1}, a_{p-1,1}, \ldots, a_{1,p-1}, a_{p-1,p}, a_{p,2}, a_{2,1}, a_{2,2}, a_{2,p-1}, a_{p-1,p-1}, a_{p-1,2}, \ldots, a_{p,p-2}, a_{p,p-2}+1, a_{p,p-1}+1, a_{p,p}+1, \frac{p}{2}+1) \top$.

Under this identification, $\sigma$ acts on $\mathbb{R}^n$ by the $n \times n$ block matrix

$$\begin{pmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}.$$  

**N.B.:** $\sigma$-invariance of $f_\theta$ implies that columns 1–4, 5–8, \ldots, $(n - 3)$–$n$ of $M$ coincide.
Properties of $I_{r,m \times n}^G \subset M_{r,m \times n}$

$G = \langle \sigma_1, \ldots, \sigma_g \rangle \leq S_n$

$\sigma_i = \pi_{i,1} \circ \cdots \circ \pi_{i,k_i}, \ i = 1, \ldots, g$

a permutation group

decomposition into pairwise disjoint cycles $\pi_i$

Reduction to cyclic case

There exists $\sigma \in S_n$ such that $I_{r,m \times n}^G = I_{r,m \times n}^\sigma$. Any $\sigma$ for which $P(\sigma)$ is the finest common coarsening of $P(\sigma_1), \ldots, P(\sigma_g)$ does the job!

Proposition

Let $G = \langle \sigma \rangle \leq S_n$ be cyclic, and $\sigma = \pi_1 \circ \cdots \circ \pi_k$ its decomposition into pairwise disjoint cycles $\pi_i$. The variety $I_{r,m \times n}^\sigma$ is isomorphic to the determinantal variety $M_{\min(r,k),m \times k}$ via a linear isomorphism $\psi_P(\sigma): I_{r,m \times n}^\sigma \rightarrow M_{\min(r,k),m \times k}$. 

deleting repeated columns

Via that, we can determine $\dim(I_{r,m \times n}^\sigma)$, $\deg(I_{r,m \times n}^\sigma)$, and $\Sing(I_{r,m \times n}^\sigma)$.

Example ($m = 2, \ n = 5, \ r = 1$)

Let $\sigma = (1\ 3\ 4)(2\ 5) \in S_5$ and hence $k = 2$. Any invariant matrix $M \in M_{2 \times 5}(\mathbb{R})$ is of the form $\begin{pmatrix} a & c & a & b & c \\ b & d & b & b & d \end{pmatrix}$ for some $a, b, c, d \in \mathbb{R}$. The rank constraint $r = 1$ imposes that $(c, d) = \lambda \cdot (a, b)^\top$ for some $\lambda \in \mathbb{R}$, where we assume that $(a, b) \neq (0, 0)$. Then

$$
\psi_P(\sigma): \begin{pmatrix} a & \lambda a & a & a & \lambda a \\ b & \lambda b & b & b & \lambda b \end{pmatrix} \mapsto \begin{pmatrix} a & \lambda a \\ b & \lambda b \end{pmatrix}.
$$
Parameterizing invariance & network design

\[ S_n \ni \sigma = \pi_1 \circ \cdots \circ \pi_k, \quad P(\sigma) = \{A_1, \ldots, A_k\} \]

Invariance of \( M \in \mathcal{M}_{m \times n} \): forces columns \( \{m_j\}_{j \in A_i} \) to coincide. For each \( i \), remember representative \( m_{A_i} \) so that

\[ \psi_{P(\sigma)}(M) = (m_{A_1} | \cdots | m_{A_k}) \in \mathcal{M}_{m \times k}. \]

Parameterization

Any \( \sigma \)-invariant \( M \in \mathcal{M}_{m \times n} \) of rank \( k \) factorizes as

\[ M = \psi_{P(\sigma)}(M) \cdot (e_{i_1} | \cdots | e_{i_n}) \]

\( i \)-th standard unit vector in column \( j \) for all \( j \in A_i \)

Fibers of multiplication map

Let \( r \leq \min(m, n) \). Denote by \( \mu : \mathcal{M}_{m \times r} \times \mathcal{M}_{r \times n}, \quad (A, B) \mapsto A \cdot B \). If \( \text{rank}(M) = r \) and \( M = \mu(A, B) \) for some \( A, B \), then the fiber of \( \mu \) over \( M \) is

\[ \mu^{-1}(M) = \left\{ \left( A T^{-1}, TB \right) \mid T \in \text{GL}_n(\mathbb{C}) \right\} \subset \mathcal{M}_{m \times r} \times \mathcal{M}_{r \times n}. \]
Learning invariant linear functions with autoencoders

\[ S_n \ni \sigma \quad \text{permutation splitting into disjoint cycles } \pi_1 \circ \cdots \circ \pi_k \]

\[ P(\sigma) \quad \text{induced partition } \{A_1, \ldots, A_k\} \text{ of } [n] \]

\[ E_{P(\sigma)} \quad \text{the } k \times n \text{ matrix with } e_i \text{ in column } j \text{ for all } j \in A_i \]

Proposition

Let \( M \) be invariant under \( \sigma \) and of rank \( k \). Any factorization \( M = A \cdot B \) is of the form

\[
(A, B) \in \left\{ \left( \psi_{P(\sigma)}(M) \cdot T^{-1}, T \cdot E_{P(\sigma)} \right) \mid T \in \text{GL}_n \right\}.
\]

This parameterization imposes a weight sharing property on the encoder!

Proposition

Let \( \sigma \in S_n \) consist of \( k \) disjoint cycles and let \( r \leq k \). Consider the linear autoencoder \( \mathbb{R}^n \to \mathbb{R}^r \to \mathbb{R}^n \) with fully-connected dense decoder \( \mathbb{R}^r \to \mathbb{R}^n \) and encoder \( \mathbb{R}^n \to \mathbb{R}^r \), with \( \sigma \)-weight sharing on the encoder. Its function space is \( \mathcal{I}_{r,n \times n}(\mathbb{R}) \).
Example

Let \( m = n = 5, \ r = 2 \) and \( \sigma = (1\ 3\ 4)(2\ 5) \in S_5 \). If a matrix \( M = AB \in I_{2,5 \times 5}^\sigma \) is invariant under \( \sigma \), the encoder factor \( B \) has to fulfill the following weight sharing property:

\[ \text{Figure: } \text{The } \sigma \text{-weight sharing property imposed on the encoder.} \]
Euclidean distance degree

Motivation: complexity during and after training

1. For an arbitrary learned function, find a nearest invariant function.

Definition

The **Euclidean distance (ED) degree** of an algebraic variety \( \mathcal{X} \) in \( \mathbb{R}^N \) is the number of complex critical points of the squared Euclidean distance from \( \mathcal{X} \) to a general point outside the variety. It is denoted by \( \operatorname{EDdegree}(\mathcal{X}) \).

Examples: \( \operatorname{EDdegree}({\text{circle}}) = 2 \), \( \operatorname{EDdegree}({\text{ellipse}}) = 4 \).

ED degree of \( \mathcal{M}_{r,m\times n}(\mathbb{R}) \) and \( \mathcal{I}_{r,m\times n}(\mathbb{R}) \)

Let \( \sigma = \pi_1 \circ \cdots \circ \pi_k \in S_n \) and \( r \leq \min(m,n) \). Then

- \( \operatorname{EDdegree}(\mathcal{M}_{r,m\times n}(\mathbb{R})) = \binom{\min(m,n)}{r} \),
- \( \operatorname{EDdegree}(\mathcal{I}_{r,m\times n}(\mathbb{R})) = \operatorname{EDdegree}(\mathcal{M}_{\min(r,k),m\times k}(\mathbb{R})) = \binom{\min(m,k)}{\min(r,k)} \).

Equivariant linear autoencoders

\[ f_\theta : \mathbb{R}^n \rightarrow \mathbb{R}^r \rightarrow \mathbb{R}^n \quad r < n \]

\[ G = \langle \sigma \rangle \leq S_n \quad \text{a cyclic permutation group generated by a single } \sigma \in S_n \]

Equivariance under \( \sigma \): \( f_\theta \circ \sigma = \sigma \circ f_\theta \).

For matrices: \( M \) equivariant iff \( MP_\sigma = P_\sigma M \).\footnote{commutator of \( P_\sigma \)}

In- and output

\( \diamond n = p^2 : p \times p \) image with real pixels \quad \( \diamond n = p^3 : \) cubic 3D scenery

Finding good bases

Exploiting similarity transforms of the form

\[ P_\sigma = \begin{pmatrix}
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0
\end{pmatrix} \sim T_1 \quad \begin{pmatrix}
0 & 0 & 1 \\
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1 \\
0 & 1 & 0
\end{pmatrix} \sim T_2 \quad \begin{pmatrix}
1 & \zeta_3 & \zeta_3^2 & 1 & \zeta_3^2 \cdot \zeta_3 \\
\zeta_3 & \zeta_3^2 & 1 & \zeta_3^2 & 1 \\
\zeta_3 & 1 & \zeta_3^2 & \zeta_3^2 \cdot \zeta_3 & 1 \\
1 \cdot \zeta_3 & \zeta_3^2 \cdot \zeta_3 & 1 \cdot \zeta_3^2 & \zeta_3^2 \cdot \zeta_3 & 1 \cdot \zeta_3^2 \\
1 \cdot \zeta_3 & \zeta_3^2 \cdot \zeta_3 & 1 \cdot \zeta_3^2 & \zeta_3^2 \cdot \zeta_3 & 1 \cdot \zeta_3^2
\end{pmatrix}
\]

Second base change involves complex Vandermonde matrices. \footnote{EDdegree not preserved!}
Finding good bases

After a real, orthogonal base change $Q_{\sigma}$, the rotation $\sigma \in S_9$ is represented by

$$l_3 \oplus (-l_2) \oplus \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \oplus \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}.$$

Matrices that commute with it:

$$\begin{pmatrix}
\alpha_{11} & \alpha_{12} & \alpha_{13} \\
\alpha_{21} & \alpha_{22} & \alpha_{23} \\
\alpha_{31} & \alpha_{32} & \alpha_{33} \\
0 & \beta_{12} & \beta_{22} \\
& \beta_{21} & \beta_{23} \\
0 & 0 & 0
\end{pmatrix}.$$

Realization map

$$\mathcal{R}: \mathbb{C} \rightarrow \left\{ \begin{pmatrix} a & -b \\ b & a \end{pmatrix} \mid a, b \in \mathbb{R} \right\}, \quad z \mapsto \begin{pmatrix} \Re(z) & -\Im(z) \\ \Im(z) & \Re(z) \end{pmatrix}.$$
Characterizing equivariance

Proposition

There is a **one-to-one correspondence** between the irreducible components of $E_{r,n \times n}(\mathbb{R})$ that contain a matrix of rank $r$ and the non-negative integer solutions $r = (r_l, m)$ of

$$r_{1,1} + r_{2,1} + \sum_{l \geq 3} \sum_{m \in (\mathbb{Z}/l\mathbb{Z})^\times, \frac{1}{2} < \frac{m}{l} < 1} 2 \cdot r_l, m = r,$$

where $0 \leq r_l, m \leq d_l$.

$d_l$ the dimension of the eigenspace of $P_\sigma$ of the eigenvalue $\zeta_l = e^{2\pi i / l}$

The irreducible component $E_{r,n \times n}^{\sigma,r}(\mathbb{R})$ corresponding to such an integer solution $r$ after the real orthogonal base change $Q_\sigma$ is

$$\mathcal{M}_{r_{1,1}, d_1 \times d_1}(\mathbb{R}) \times \mathcal{M}_{r_{2,1}, d_2 \times d_2}(\mathbb{R}) \times \prod_{l \geq 3} \prod_{m \in (\mathbb{Z}/l\mathbb{Z})^\times, \frac{1}{2} < \frac{m}{l} < 1} \mathcal{R}(\mathcal{M}_{r_l, m, d_l \times d_l}(\mathbb{C})).$$

Via that: $\dim \checkmark$ $\deg \checkmark$ $\text{EDdegree} \checkmark$ $\text{Sing} \checkmark$

Consequence

Equivariant linear functions can **not** be parameterized by a single neural network! One needs to parameterize each irreducible component of $E_{r,n \times n}^\sigma$ separately.
The real irreducible component \((\mathcal{E}^\sigma_{3,9} \times 9) \sim Q^\sigma\) with \(r = (1, 0, 1)\) is

\[
\mathcal{M}_{1,3 \times 3}(\mathbb{R}) \times \mathcal{M}_{0,2 \times 2}(\mathbb{R}) \times \mathcal{R}(\mathcal{M}_{1,2 \times 2}(\mathbb{C}))
\]

Every matrix in this component can be obtained as product of a \(9 \times 3\) and a \(3 \times 9\) matrix of the form \(* \in \mathbb{R}, * \in \mathbb{C}\)

\[
\begin{pmatrix}
* & * & * & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \mathcal{R}(*) & * \\
0 & 0 & 0 & 0 & 0 & \mathcal{R}(*) & * \\
\end{pmatrix}^\top 
\begin{pmatrix}
* & * & * & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \mathcal{R}(*) & * \\
0 & 0 & 0 & 0 & 0 & \mathcal{R}(*) & * \\
\end{pmatrix}
\]

**Figure:** Weight-sharing of the encoder and decoder matrices. Edges of the same color share the same weight—and differ by sign, in case one of the edges is dashed.
Training on MNIST

MNIST
\[ \mathbb{R}^{784} \rightarrow \mathbb{R}' \rightarrow \mathbb{R}^{784} \]
\[ \sigma \in S_{784} \]

60,000 images of handwritten digits, size $28 \times 28$ each
linear autoencoder, bottleneck $r = 99$
permutation of pixels: translating to the right

Figure: Top row: Nine samples from the MNIST [5] test dataset, shifted horizontally randomly by up to six pixels. Middle row: Output of a linear equivariant autoencoder designed to be equivariant under horizontal translations. The network architecture is determined by the integer vector $r$. Bottom row: Output of a dense linear autoencoder with $r = 99$ without equivariance imposed.

Irreducible components

\( E_{784 \times 784}^{\sigma} \) has many irreducible components: \( 72,425,986,088,826 \)

Choose component \( E_{784 \times 784}^{\sigma,r} \) corresponding to

\[
\begin{align*}
    r &= (r_{1,1}, r_{28,27}, r_{14,13}, r_{28,25}, r_{7,6}, r_{28,23}, r_{14,11}, r_{4,3}, r_{7,5}, r_{28,19}, r_{14,9}, r_{28,17}, r_{7,4}, r_{28,15}, r_{2,1}) \\
    &= (13, 10, 9, 8, 7, 5, 3, 1, 0, 0, 0, 0, 0, 0).
\end{align*}
\]

Training loss

<table>
<thead>
<tr>
<th></th>
<th>Equivariant</th>
<th>equal-rank equivariant</th>
<th>high-pass equivariant</th>
<th>non-equivariant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss</td>
<td>0.0082</td>
<td>0.0206</td>
<td>0.1063</td>
<td>0.0057</td>
</tr>
</tbody>
</table>

Table: Comparison of average square loss values per pixel between linear equivariant and non-equivariant autoencoders on the MNIST test dataset.

Efficiency of equivariant architecture

Significant drop in number of parameters compared to general dense linear autoencoder!

\[
2 \cdot 99 \cdot 784 = 155,232 \quad \rightarrow \quad 5,544 = 2 \cdot (28 \cdot 13 + 2 \cdot 28 \cdot (10 + 9 + 8 + 7 + 5 + 3 + 1))
\]

Implementations in Python

Soon to be available at https://github.com/vahidshahverdi/Equivariant
Conclusion

Key points: algebraic geometry helps for...

1. a thorough study of function spaces of linear neural networks.
   fully connected, convolutional
2. understanding the training process.
   locating critical points of the loss
3. the design of neural networks.
   rank constraint, weight sharing properties
4. determining the complexity during and post training.
   ED degree of real varieties

Future work

- full characterization of equivariance
  non-cyclic permutation groups
- variation of the network architecture
  more layers, non-linear activation functions

*Tack för uppmärksamheten!*