

Singular Value Decomposition

Matrixology (Linear Algebra)—Episode 25/25

MATH 124, Spring, 2015

The Fundamental
Theorem of
Linear Algebra

Hubs and
Authorities

Approximating
matrices with SVD

Prof. Peter Dodds

Dept. of Mathematics & Statistics | Vermont Complex Systems Center
Vermont Advanced Computing Core | University of Vermont



$$\begin{bmatrix} I \\ \sqrt{\lambda(A^T)} \end{bmatrix}$$

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Episode 25/25:
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Outline

Episode 25/25:

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Decomposition

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Fundamental Theorem of Linear Algebra

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Singular Value
Decomposition

- ▶ Applies to any $m \times n$ matrix A .
- ▶ Symmetry of A and A^T .

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Where $\vec{x}$ lives:

- ▶ Row space $C(A^T) \subset R^n$.
- ▶ (Right) Nullspace $N(A) \subset R^n$.
- ▶ $\dim C(A^T) + \dim N(A) = r + (n - r) = n$
- ▶ Orthogonality: $C(A^T) \otimes N(A) = R^n$

Where $\vec{b}$ lives:

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Best solution $\vec{x}_*$ when $\vec{b} = \vec{p} + \vec{e}$:

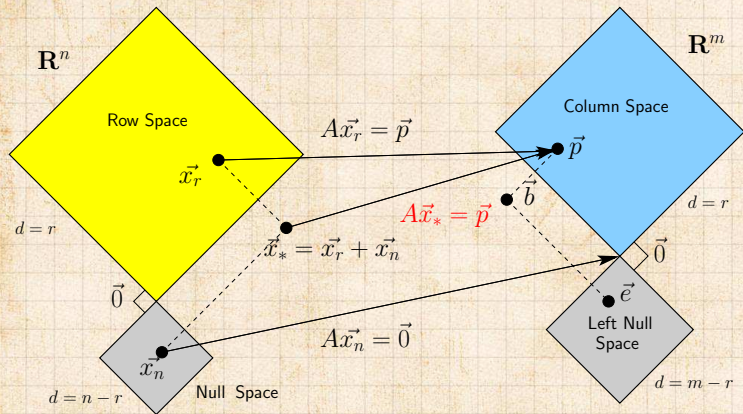
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Now we see:

- ▶ Each of the four fundamental subspaces has a 'best' orthonormal basis
- ▶ The $\hat{v}_i$ span R^n
- ▶ We find the $\hat{v}_i$ as eigenvectors of $A^T A$.
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How $A\vec{x}$ works:



$$A\hat{v}_i = \sigma_i \hat{u}_i \text{ for } i = 1, \dots, r.$$

and

$$A\hat{v}_i = \hat{0} \text{ for } i = r + 1, \dots, n.$$

► Matrix version:

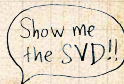
$$A = U\Sigma V^T$$

- A sends each $\hat{v}_i \in C(A^T)$ to its partner $\hat{u}_i \in C(A)$ with a positive stretch/shrink factor $\sigma_i > 0$.
- A is diagonal with respect to these bases.
- When viewed in the right way, every A is a diagonal matrix Σ .

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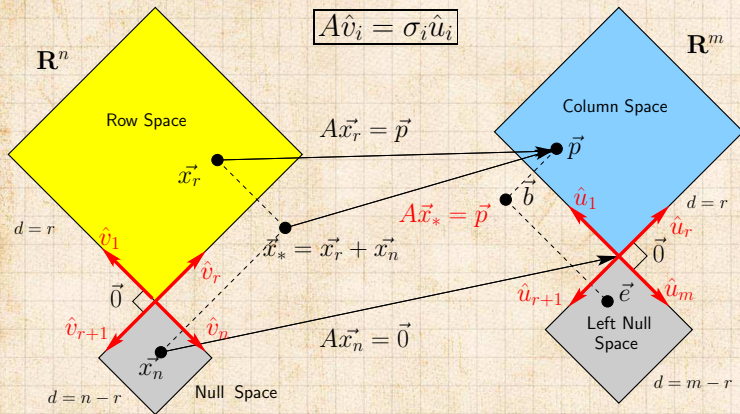
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- ▶ Idea: allow nodes in a knowledge network to have two attributes:

1. **Authority**: how much knowledge, information, etc., held by a node on a topic.
2. **Hubsness** (or **Hubbishness** or **Hubscentricity**): how well a node 'knows' where to find information on a given topic.

- ▶ Original work due to the legendary Jon Kleinberg.
- ▶ Best hubs point to best authorities.
- ▶ **Recursive**: Hubs authoritatively link to hubs, authorities hubbishly link to other authorities.
- ▶ More: look for dense links between sets of 'good' hubs pointing to sets of 'good' authorities.
- ▶ Known as the HITS algorithm (Hyperlink-Induced Topics Search).

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Singular Value
Decomposition

- ▶ Idea: allow nodes in a knowledge network to have two attributes:

1. **Authority**: how much knowledge, information, etc., held by a node on a topic.
2. **Hubness (or Hubosity or Hubbishness or Hubtasticness)**: how well a node 'knows' where to find information on a given topic.

- ▶ Original work due to the legendary Jon Kleinberg.
- ▶ Best hubs point to best authorities.
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► Give each node two scores:

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2. y_j = hub score for node j

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► We connect the scores of neighboring nodes.

► I: a good authority is linked to by good hubs.

► Means x_i should increase as $\sum_j A_{ji} y_j$ increases.

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$$x \propto A^T y \text{ and } y \propto Ax$$

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- So let's say we have

$$\vec{x} = c_1 A^T \vec{y} \text{ and } \vec{y} = c_2 A \vec{x}$$

where c_1 and c_2 must be positive.

- Above equations combine to give

$$\vec{x} = c_1 A^T c_2 A \vec{x} = \lambda A^T A \vec{x}$$

where $\lambda = c_1 c_2 > 0$.

- It's all good! we have the heart of singular value decomposition before us...

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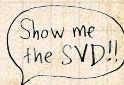
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We can do this:

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- ▶ $A^T A$ is symmetric.
- ▶ $A^T A$ is semi-positive definite so its eigenvalues are all ≥ 0 .
- ▶ $A^T A$'s eigenvalues are the square of A 's singular values.
- ▶ $A^T A$'s eigenvectors form a joyful orthogonal basis.
- ▶ The splendid Perron-Frobenius theorem  tells us that only the dominant eigenvalue's eigenvector can be chosen to have non-negative entries.
- ▶ So: linear assumption leads to a solvable system.
- ▶ What would be very good: find networks where we have independent measures of node 'importance' and see how importance is actually distributed.

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Image approximation (80x60)

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Idea: use SVD to approximate images

- ▶ Interpret elements of matrix A as color values of an image.
- ▶ Truncate series SVD representation of A :

$$A = U\Sigma V^T = \sum_{i=1}^r \sigma_i \hat{u}_i \hat{v}_i^T$$

- ▶ Use fact that $\sigma_1 \geq \sigma_2 \geq \dots \geq \sigma_r > 0$.
- ▶ Rank $r \leq \min(m, n)$.
- ▶ Rank $r \leq \#$ of pixels on shortest side.
- ▶ For color: approximate 3 matrices (RGB).

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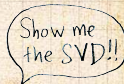


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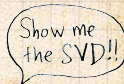
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- And now for the Exciting Scottish Fabric Image Guessing Game ...

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Image approximation (640 x 640)

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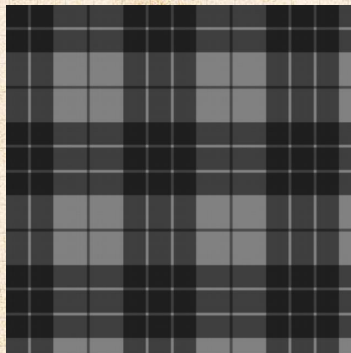
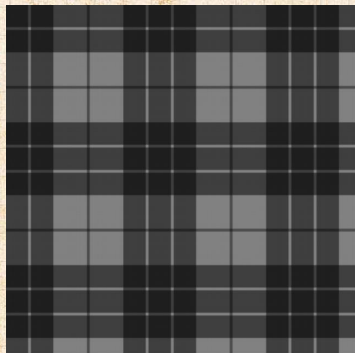
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^1 \sigma_i \hat{u}_i \hat{v}_i^T$$

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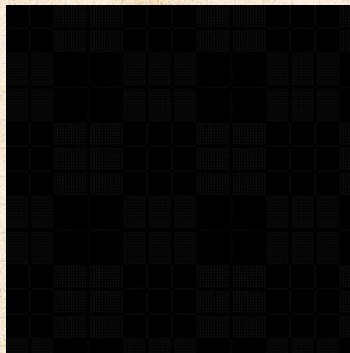
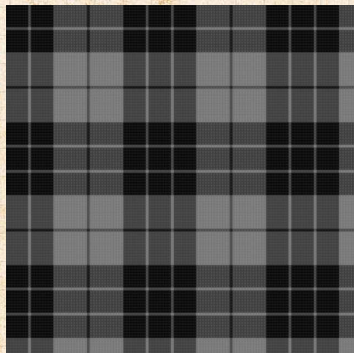
Singular Value
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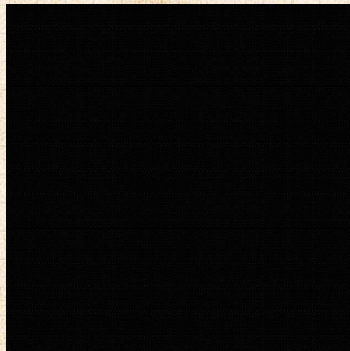
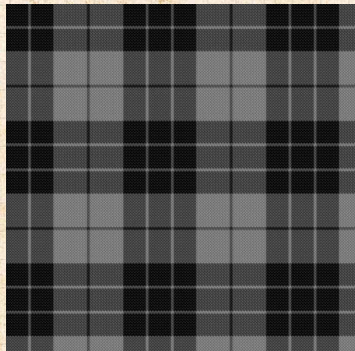
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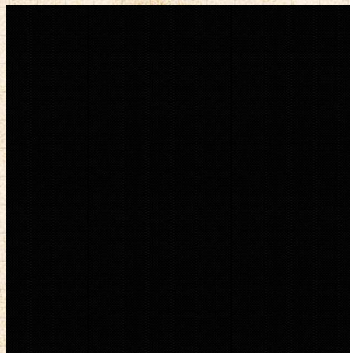
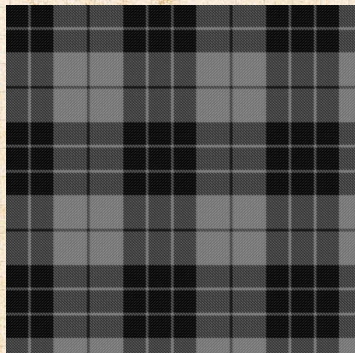
Episode 25/25:
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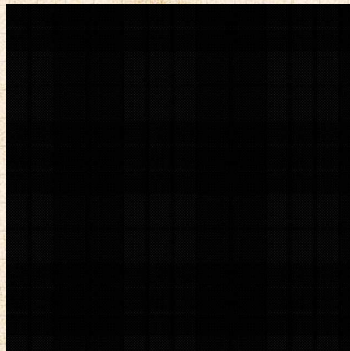
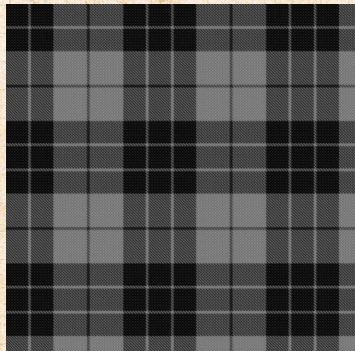
Episode 25/25:
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$$\mathbf{A} = \sum_{i=1}^5 \sigma_i \hat{u}_i \hat{v}_i^T$$

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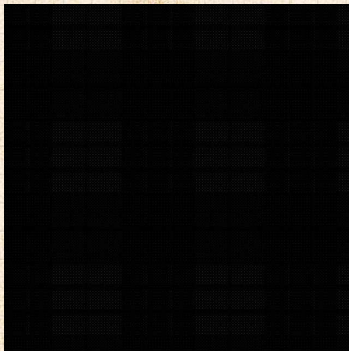
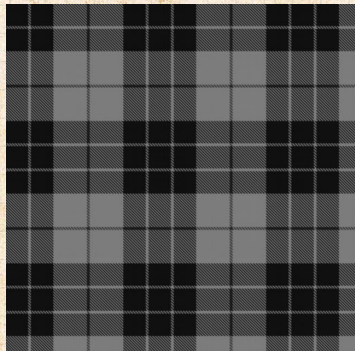
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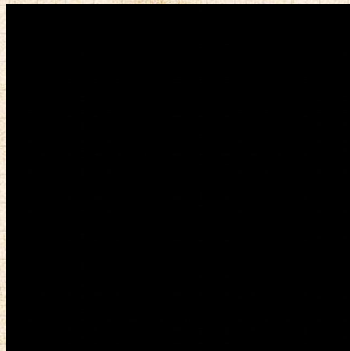
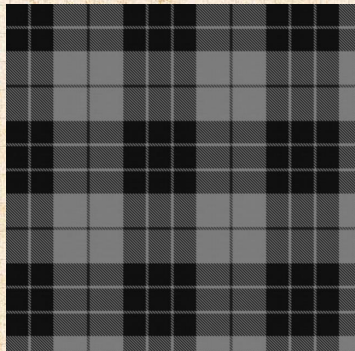
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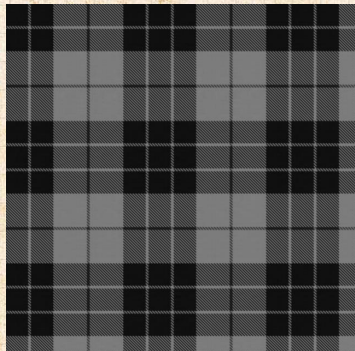
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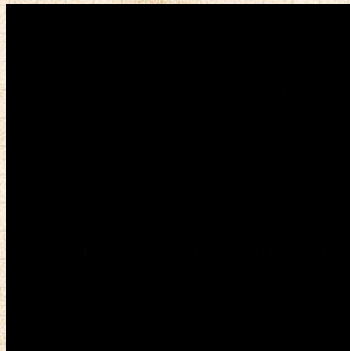
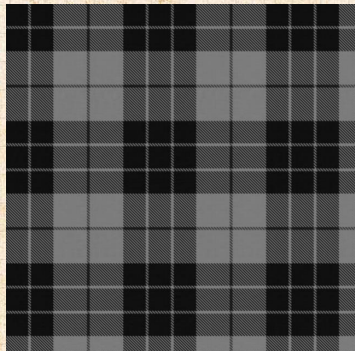
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$$\mathbf{A} = \sum_{i=1}^9 \sigma_i \hat{u}_i \hat{v}_i^T$$

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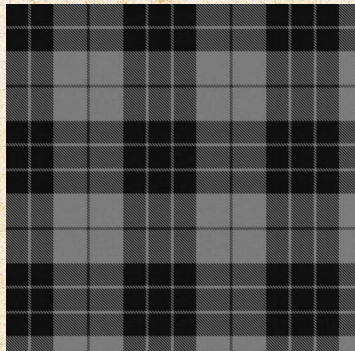
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$$\mathbf{A} = \sum_{i=1}^{10} \sigma_i \hat{u}_i \hat{v}_i^T$$



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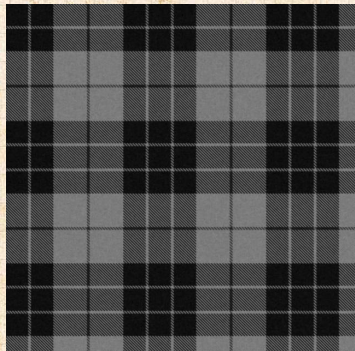
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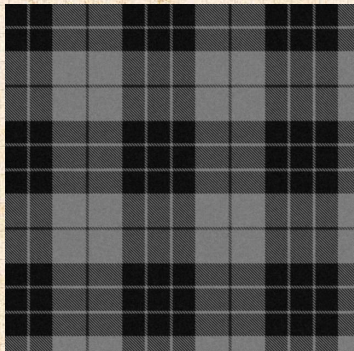
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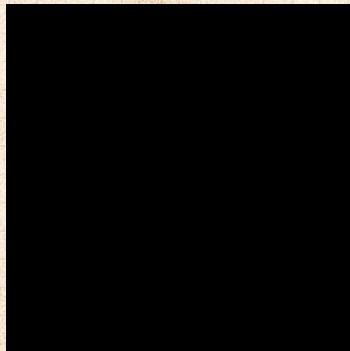
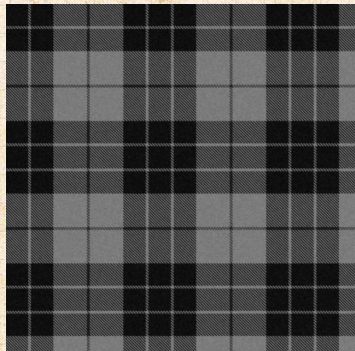
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$$\mathbf{A} = \sum_{i=1}^{640} \sigma_i \hat{u}_i \hat{v}_i^T$$

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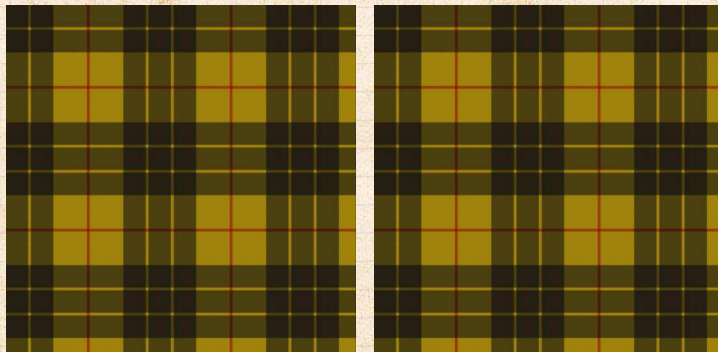
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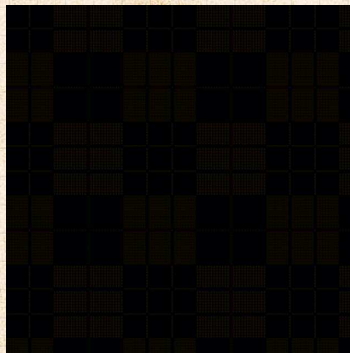
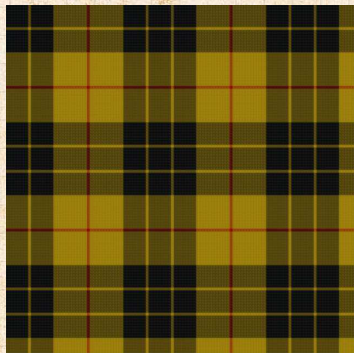
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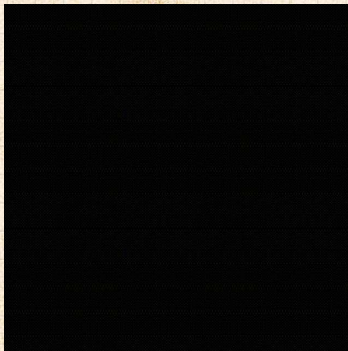
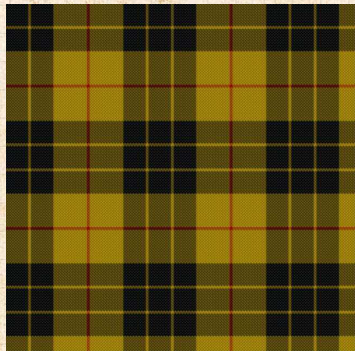
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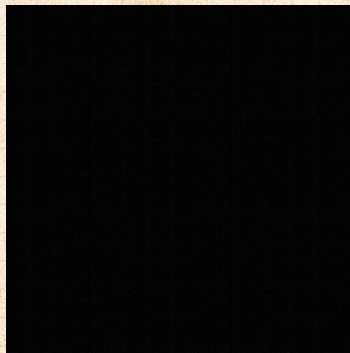
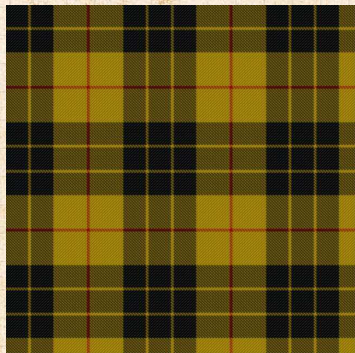
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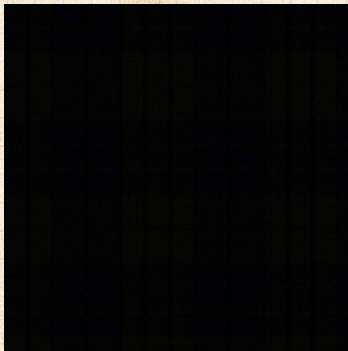
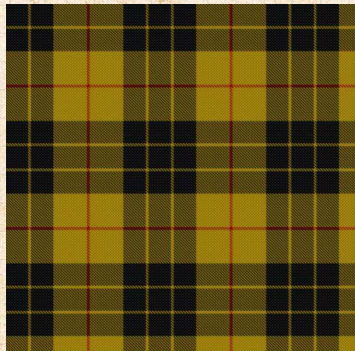
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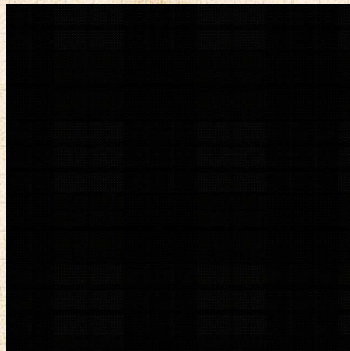
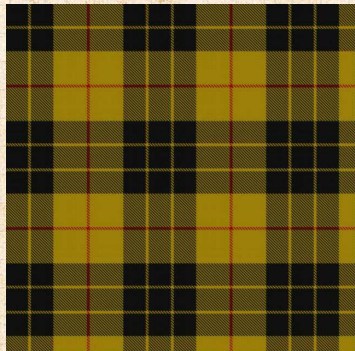
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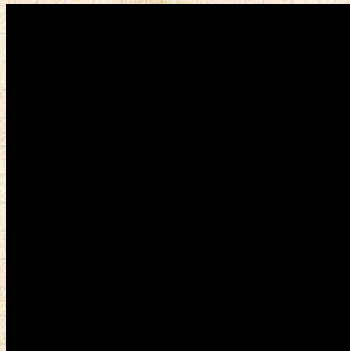
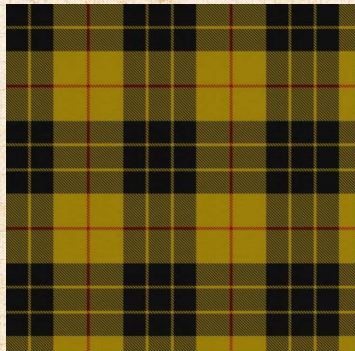
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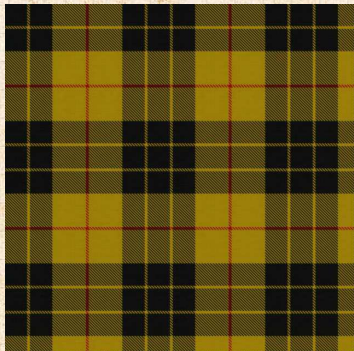


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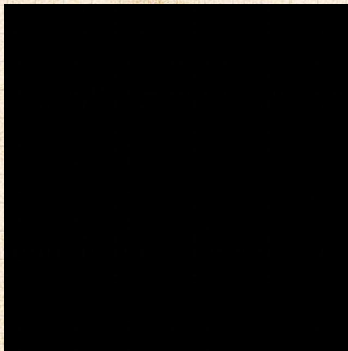
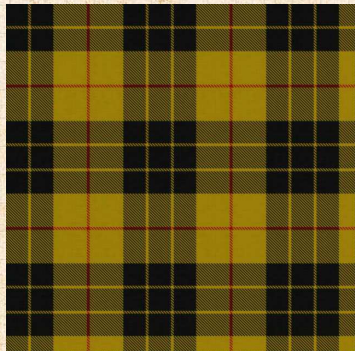
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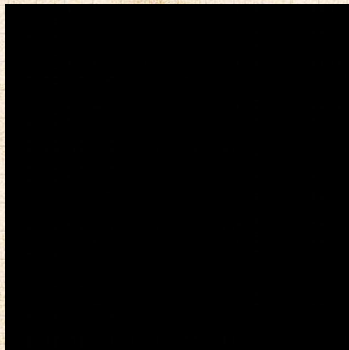
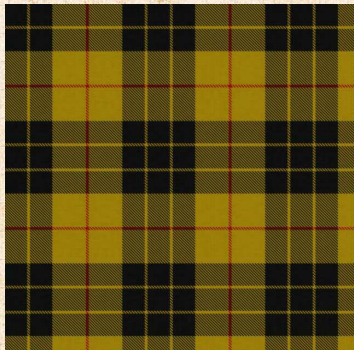


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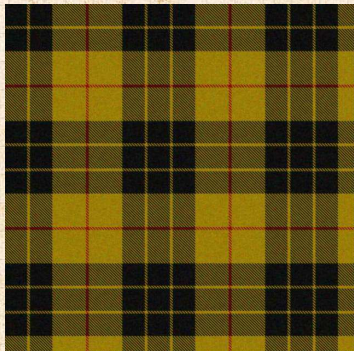
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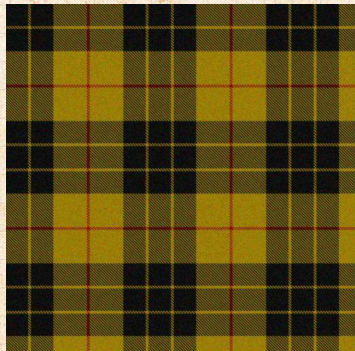
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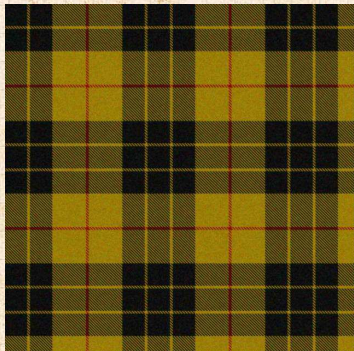


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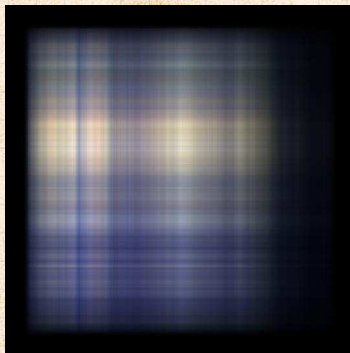
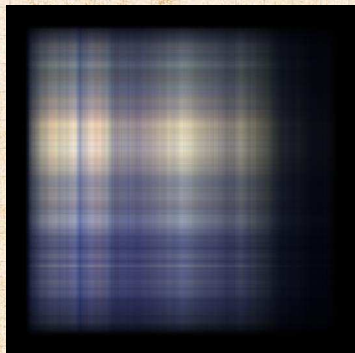
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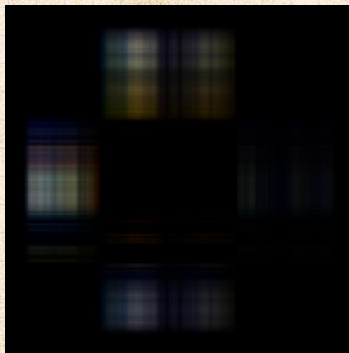
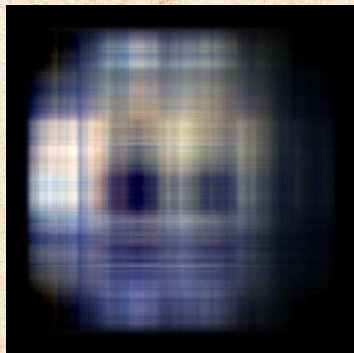
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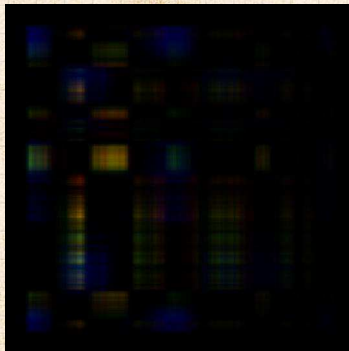
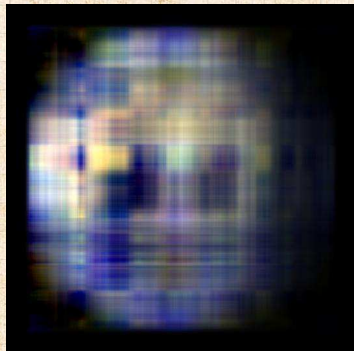
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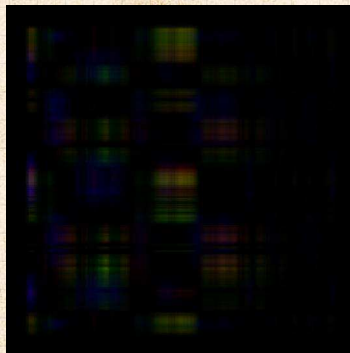
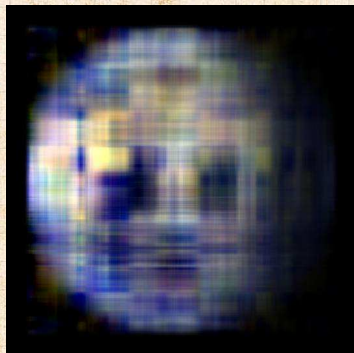
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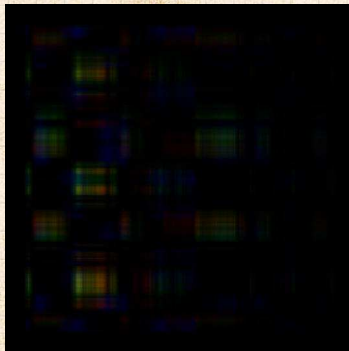
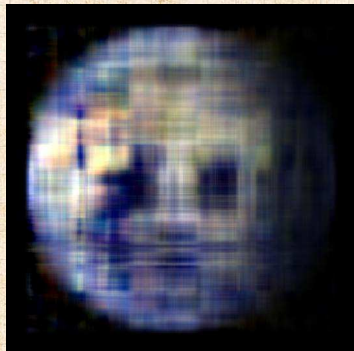
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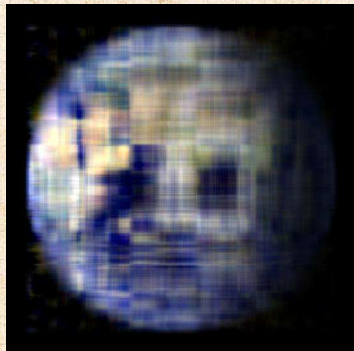
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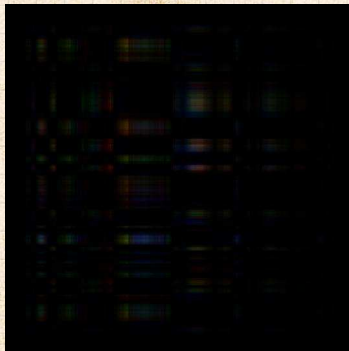
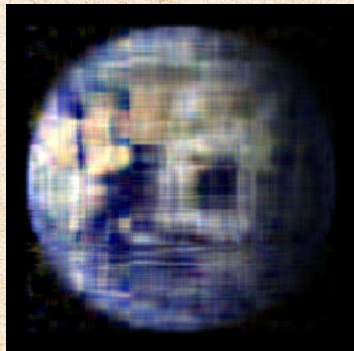
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Image approximation (540 x 540)

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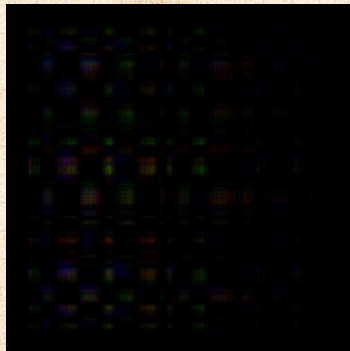
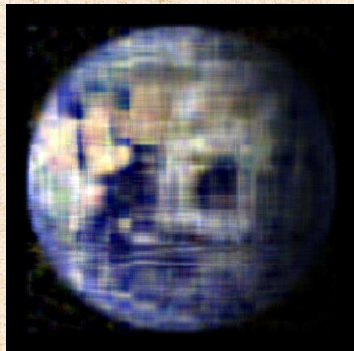
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^8 \sigma_i \hat{u}_i \hat{v}_i^T$$

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Image approximation (540 x 540)

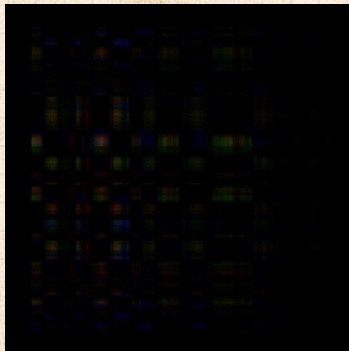
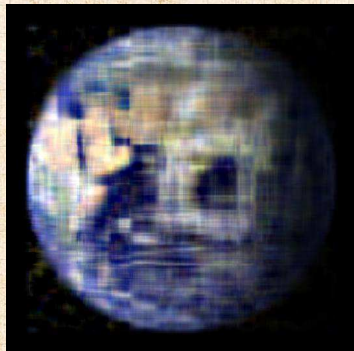
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$$\mathbf{A} = \sum_{i=1}^9 \sigma_i \hat{u}_i \hat{v}_i^T$$



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Image approximation (540 x 540)

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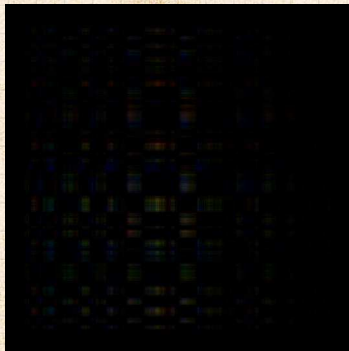
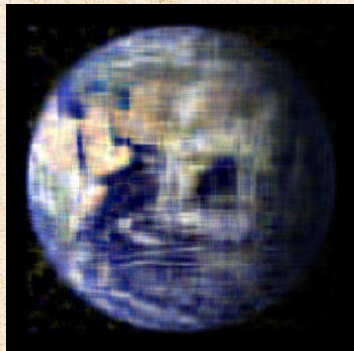
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^{10} \sigma_i \hat{u}_i \hat{v}_i^T$$

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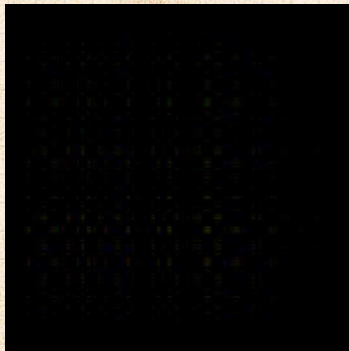
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$$\mathbf{A} = \sum_{i=1}^{20} \sigma_i \hat{u}_i \hat{v}_i^T$$



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Image approximation (540 x 540)

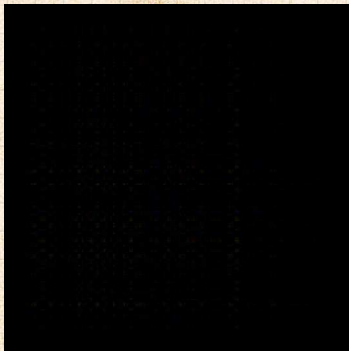
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$$\mathbf{A} = \sum_{i=1}^{30} \sigma_i \hat{u}_i \hat{v}_i^T$$



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Image approximation (540 x 540)

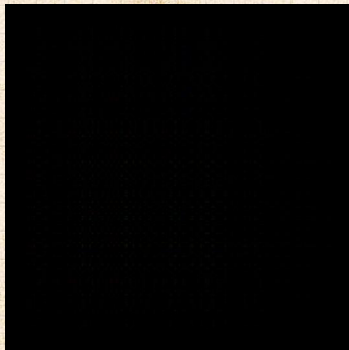
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$$\mathbf{A} = \sum_{i=1}^{40} \sigma_i \hat{\mathbf{u}}_i \hat{\mathbf{v}}_i^T$$



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Image approximation (540 x 540)

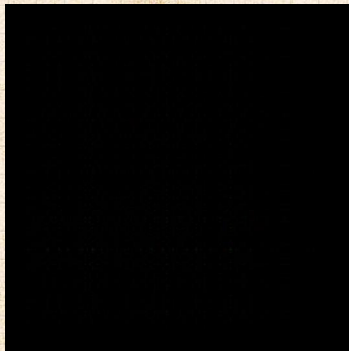
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$$\mathbf{A} = \sum_{i=1}^{50} \sigma_i \hat{u}_i \hat{v}_i^T$$



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Image approximation (540 x 540)

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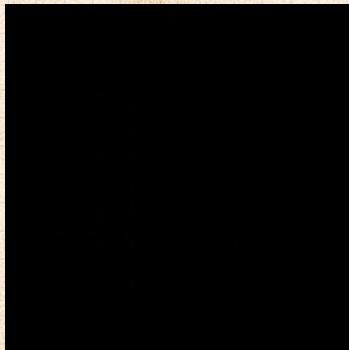
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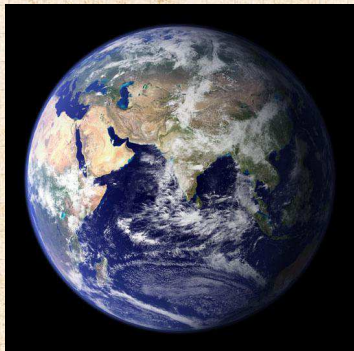
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^{250} \sigma_i \hat{u}_i \hat{v}_i^T$$

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Image approximation (540 x 540)

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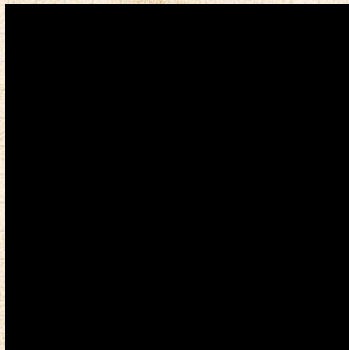
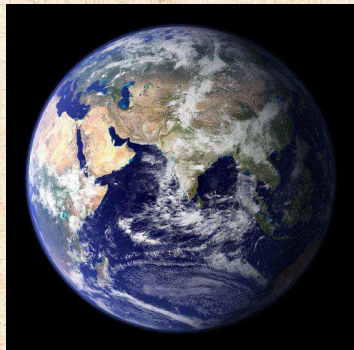
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^{480} \sigma_i \hat{u}_i \hat{v}_i^T$$

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Image approximation (80 x 60)

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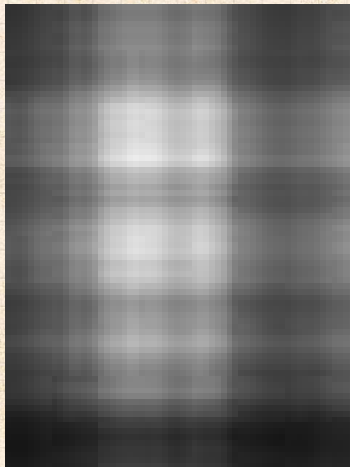
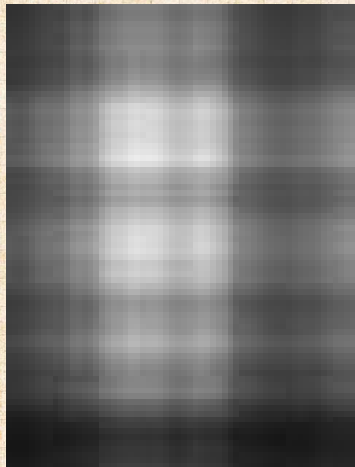
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Decomposition

$$\mathbf{A} = \sum_{i=1}^1 \sigma_i \hat{u}_i \hat{v}_i^T$$

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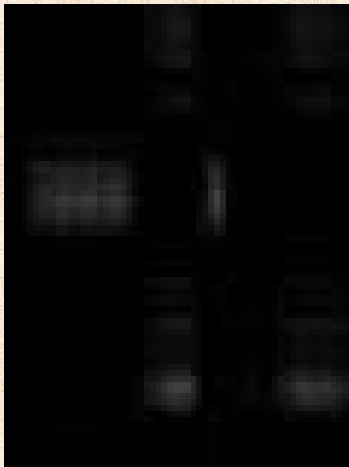
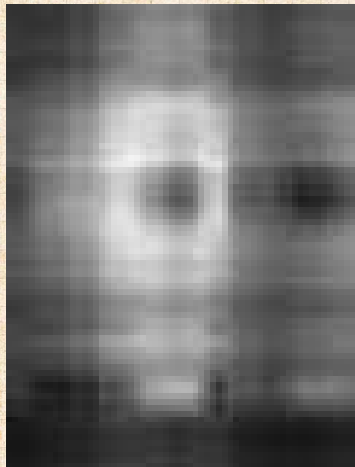
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$$\mathbf{A} = \sum_{i=1}^2 \sigma_i \hat{u}_i \hat{v}_i^T$$

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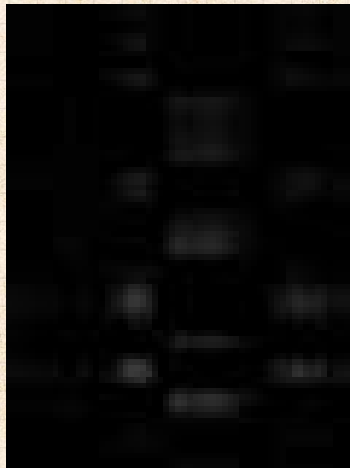
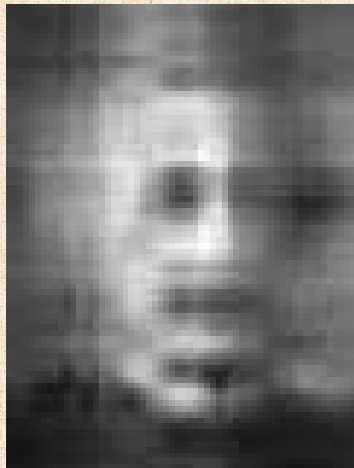
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$$\mathbf{A} = \sum_{i=1}^3 \sigma_i \hat{u}_i \hat{v}_i^T$$

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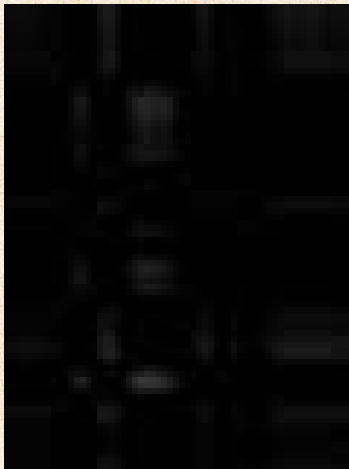
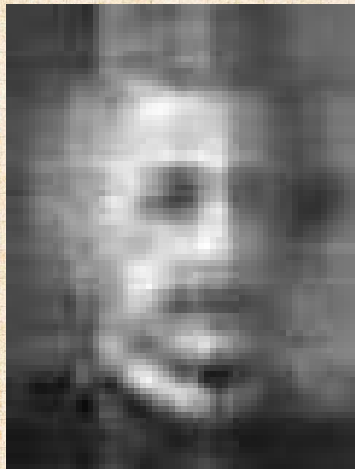
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^4 \sigma_i \hat{u}_i \hat{v}_i^T$$

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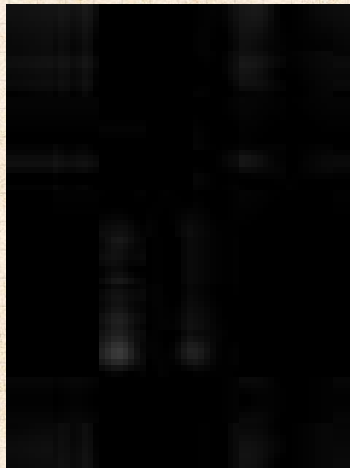
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$$\mathbf{A} = \sum_{i=1}^5 \sigma_i \hat{u}_i \hat{v}_i^T$$

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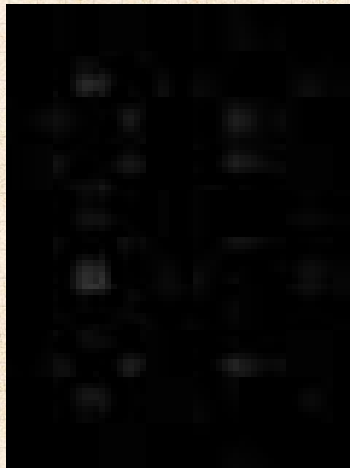
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Decomposition

$$\mathbf{A} = \sum_{i=1}^6 \sigma_i \hat{u}_i \hat{v}_i^T$$

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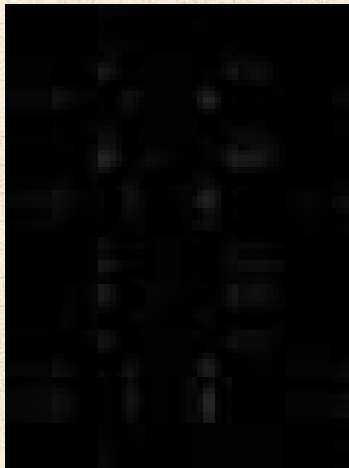
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^7 \sigma_i \hat{u}_i \hat{v}_i^T$$

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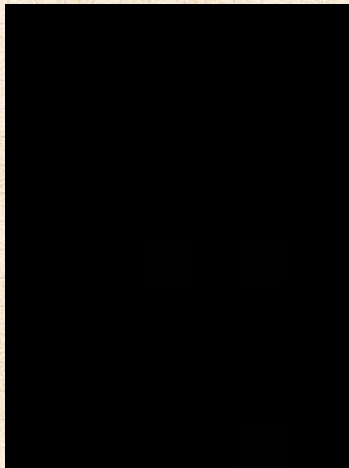
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$$\mathbf{A} = \sum_{i=1}^{30} \sigma_i \hat{u}_i \hat{v}_i^T$$

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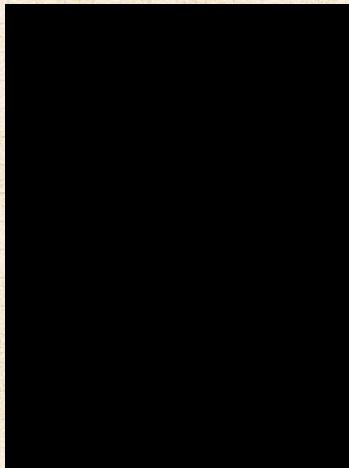
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$$\mathbf{A} = \sum_{i=1}^{40} \sigma_i \hat{u}_i \hat{v}_i^T$$

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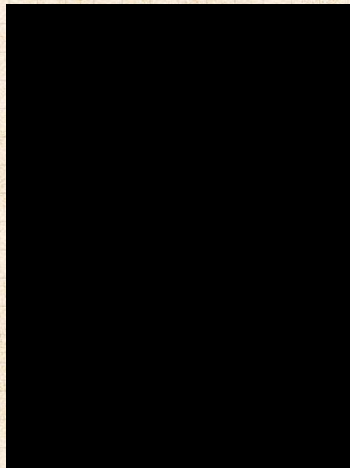
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$$\mathbf{A} = \sum_{i=1}^{50} \sigma_i \hat{u}_i \hat{v}_i^T$$

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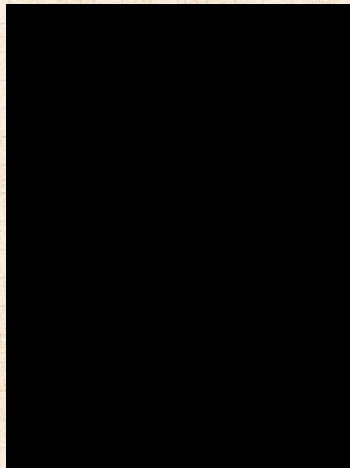
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$$\mathbf{A} = \sum_{i=1}^{60} \sigma_i \hat{u}_i \hat{v}_i^T$$

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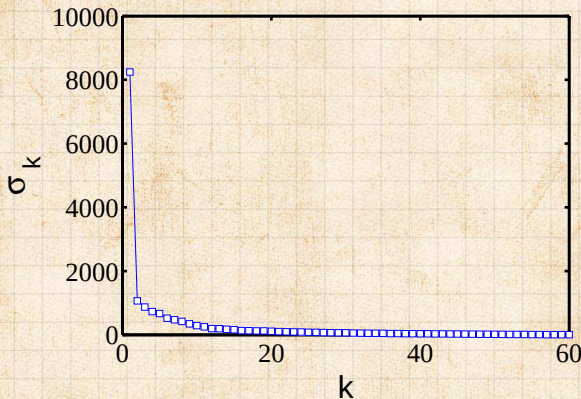
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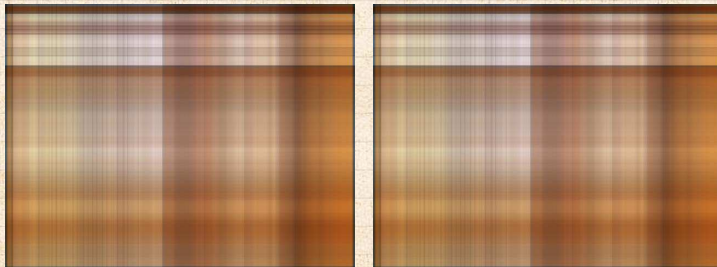
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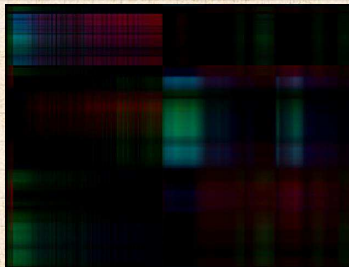
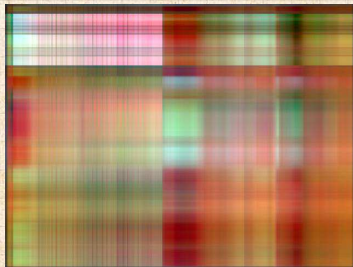
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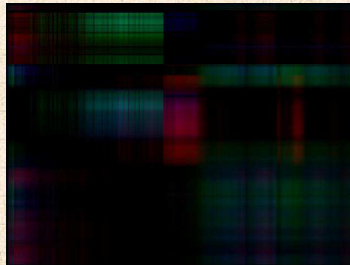
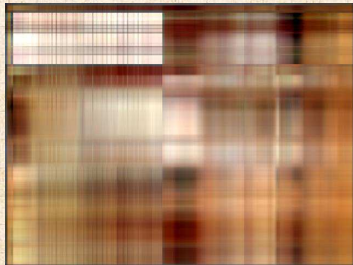
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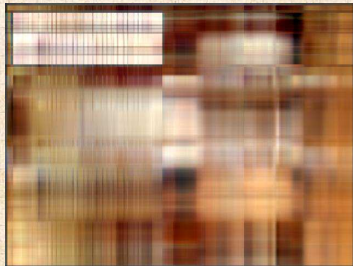
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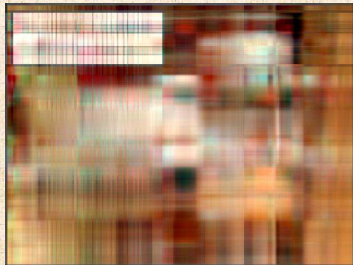
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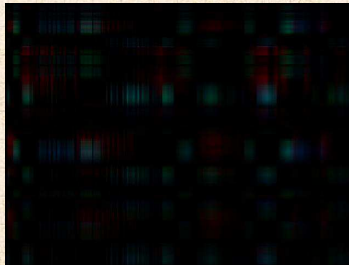
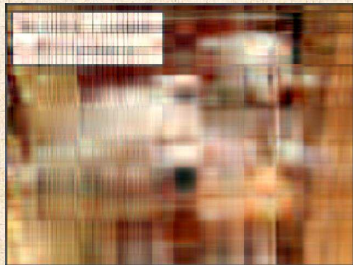
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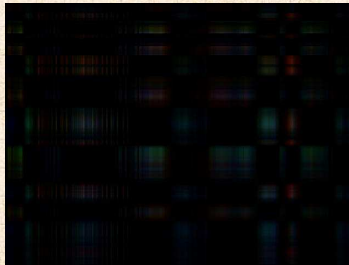
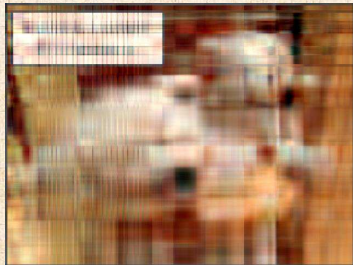
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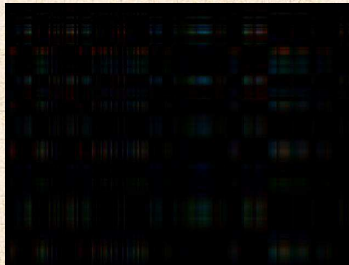
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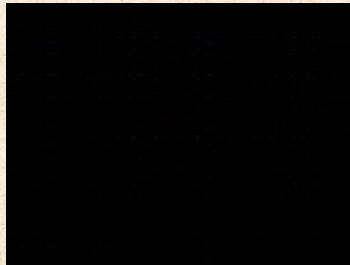
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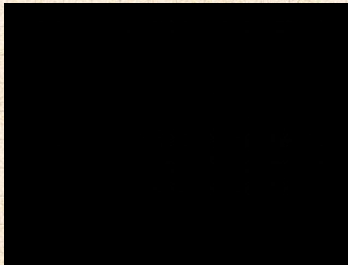
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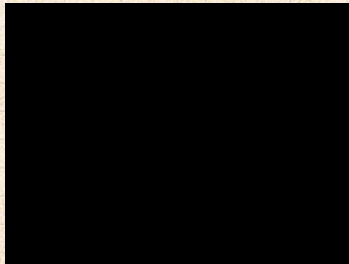
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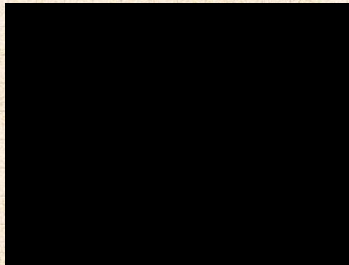
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$$\mathbf{A} = \sum_{i=1}^{480} \sigma_i \hat{u}_i \hat{v}_i^T$$



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Image approximation (640 x 640)

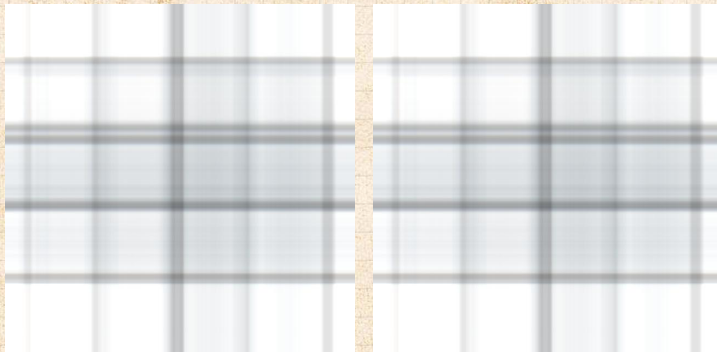
Episode 25/25:
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^1 \sigma_i \hat{u}_i \hat{v}_i^T$$

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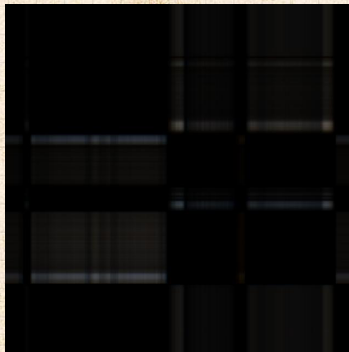
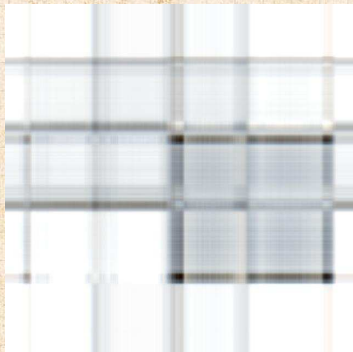
Episode 25/25:
Singular Value
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$$\mathbf{A} = \sum_{i=1}^2 \sigma_i \hat{u}_i \hat{v}_i^T$$

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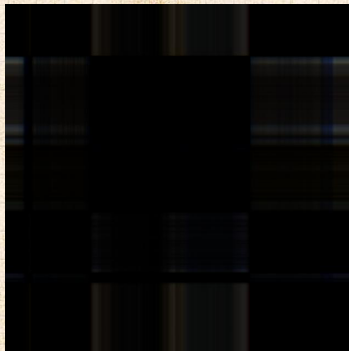
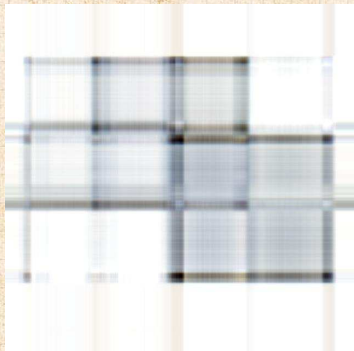
Episode 25/25:
Singular Value
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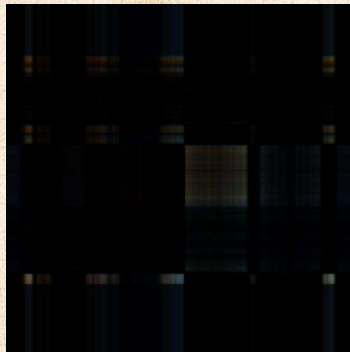
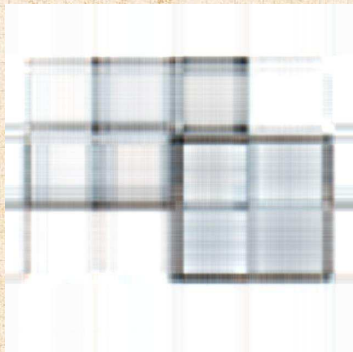
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$$\mathbf{A} = \sum_{i=1}^4 \sigma_i \hat{u}_i \hat{v}_i^T$$

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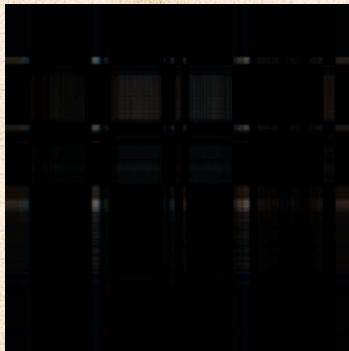
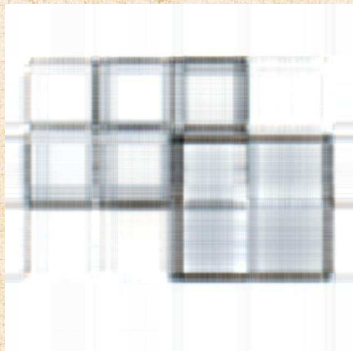
Singular Value
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$$\mathbf{A} = \sum_{i=1}^5 \sigma_i \hat{u}_i \hat{v}_i^T$$

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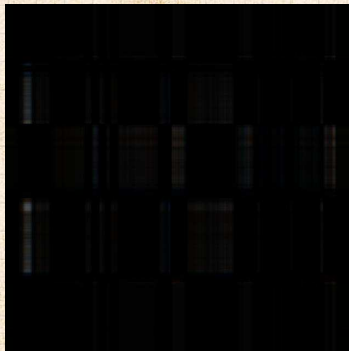
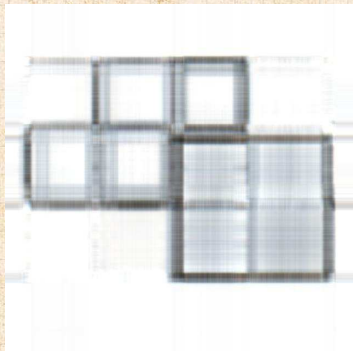
Singular Value
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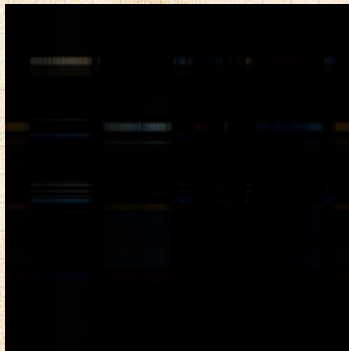
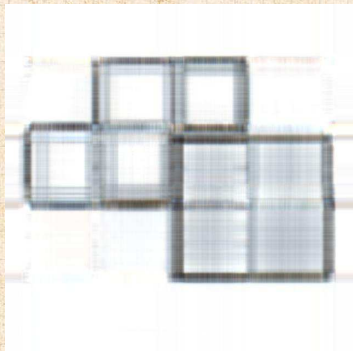
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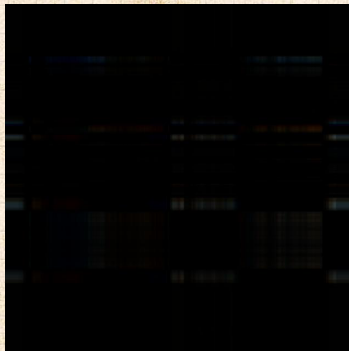
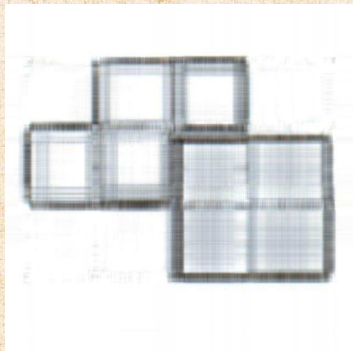
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$$\mathbf{A} = \sum_{i=1}^8 \sigma_i \hat{u}_i \hat{v}_i^T$$

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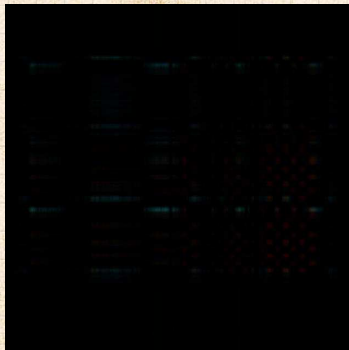
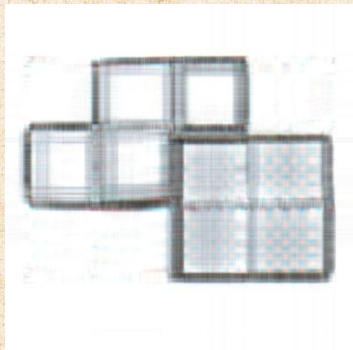
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$$\mathbf{A} = \sum_{i=1}^9 \sigma_i \hat{u}_i \hat{v}_i^T$$

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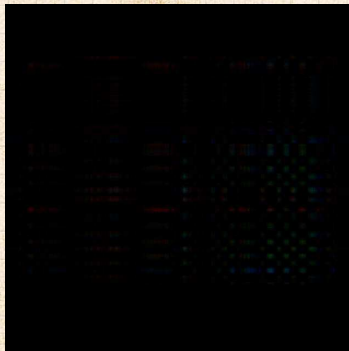
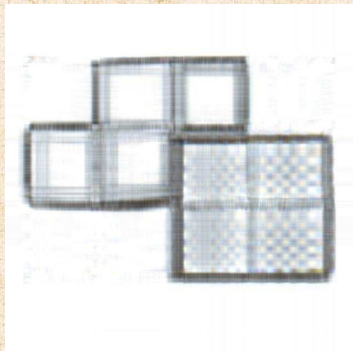
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$$\mathbf{A} = \sum_{i=1}^{10} \sigma_i \hat{u}_i \hat{v}_i^T$$

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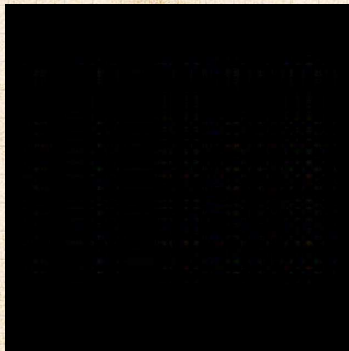
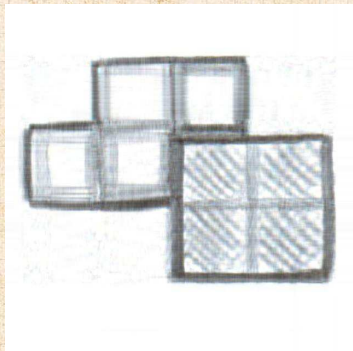
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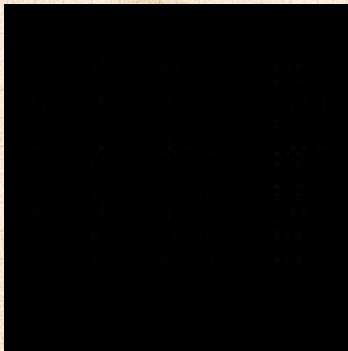
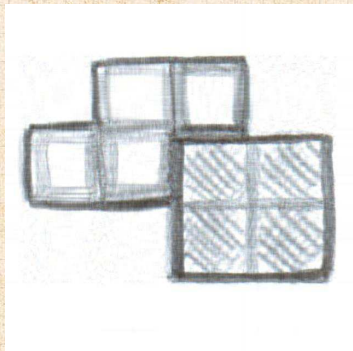
Singular Value
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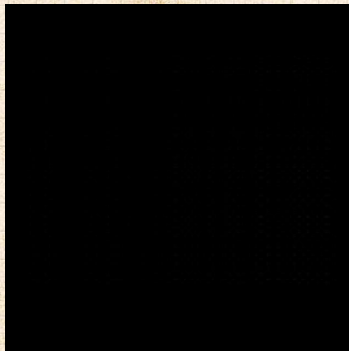
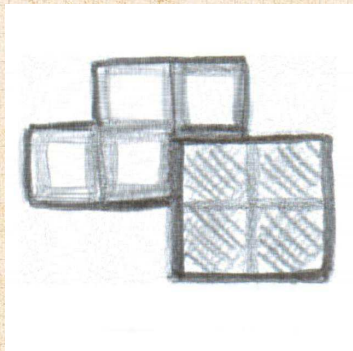
Singular Value
Decomposition

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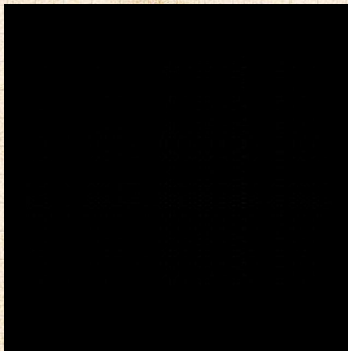
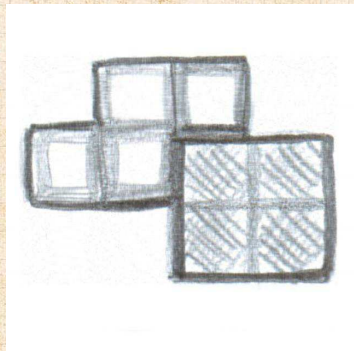
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$$\mathbf{A} = \sum_{i=1}^{50} \sigma_i \hat{u}_i \hat{v}_i^T$$

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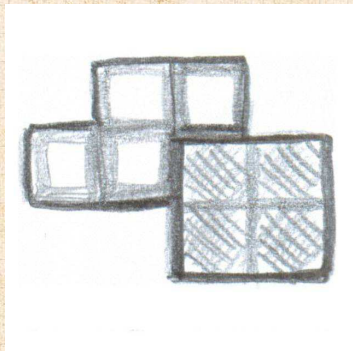
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$$\mathbf{A} = \sum_{i=1}^{100} \sigma_i \hat{u}_i \hat{v}_i^T$$

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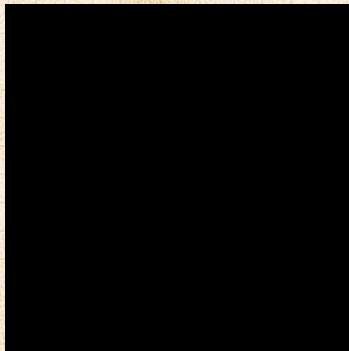
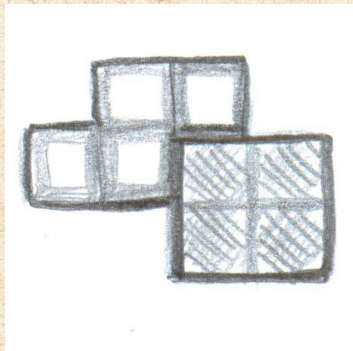
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$$\mathbf{A} = \sum_{i=1}^{300} \sigma_i \hat{u}_i \hat{v}_i^T$$

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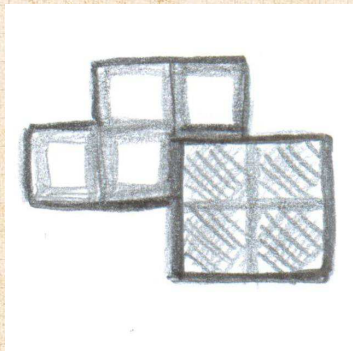
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$$\mathbf{A} = \sum_{i=1}^{470} \sigma_i \hat{u}_i \hat{v}_i^T$$

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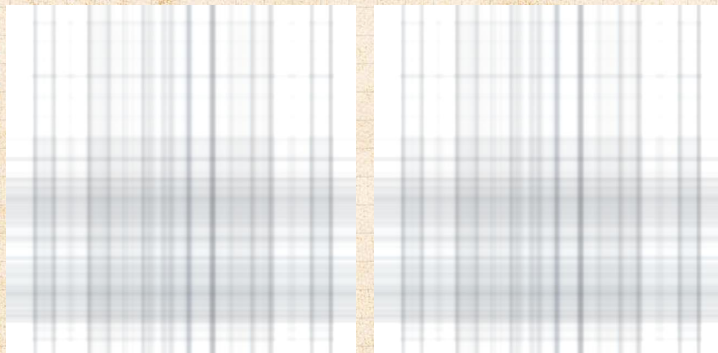
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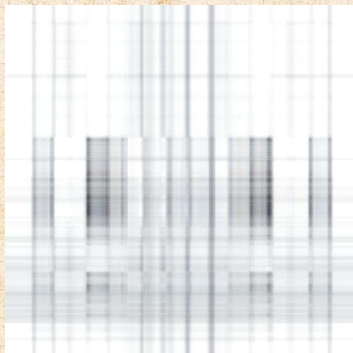
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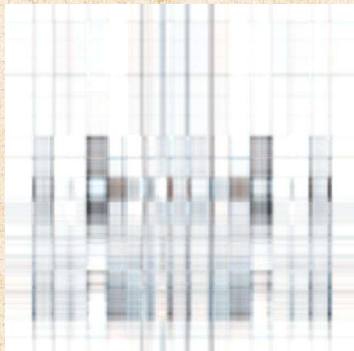
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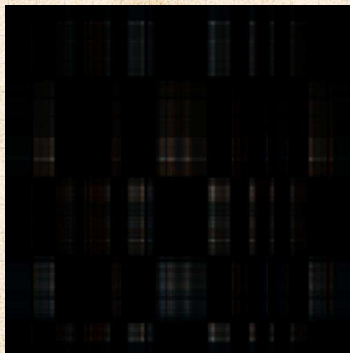
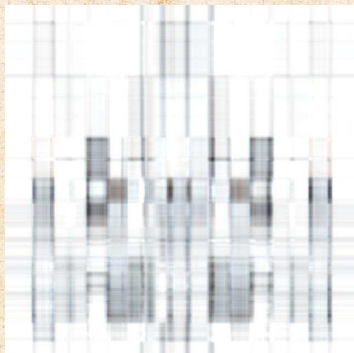
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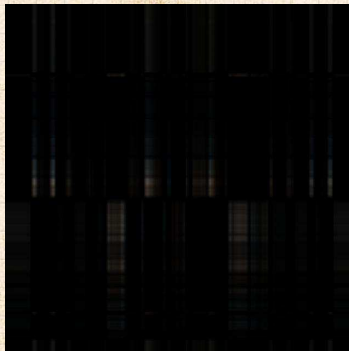
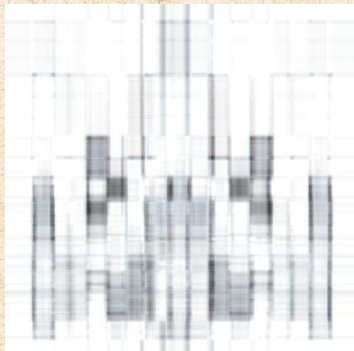
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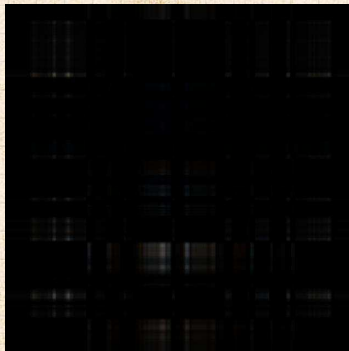
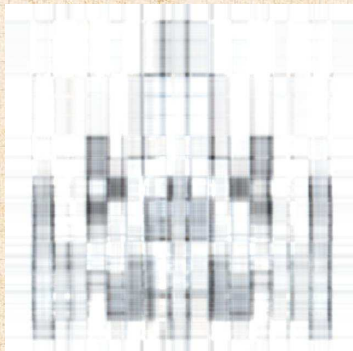
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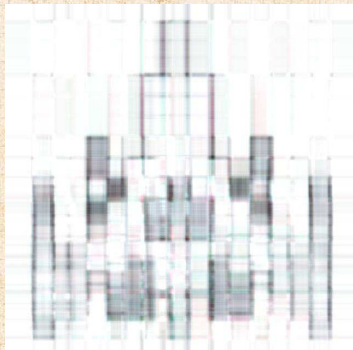


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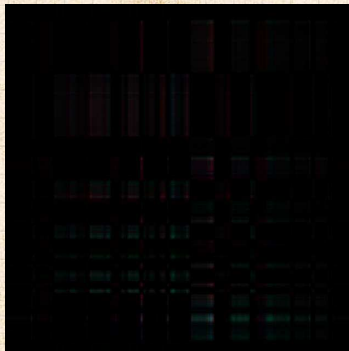
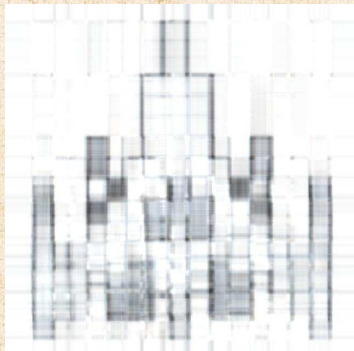
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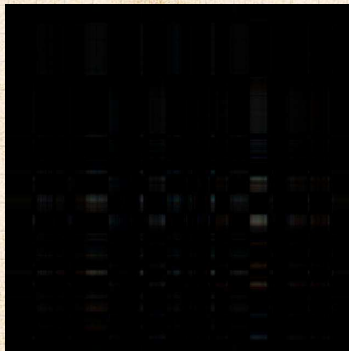
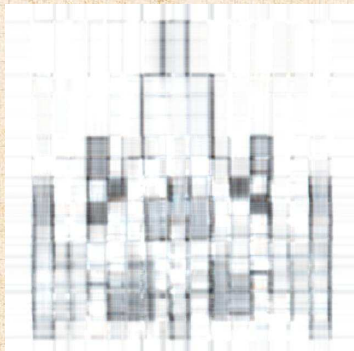
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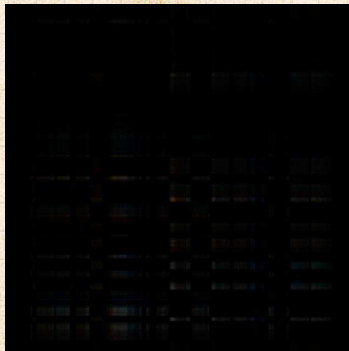
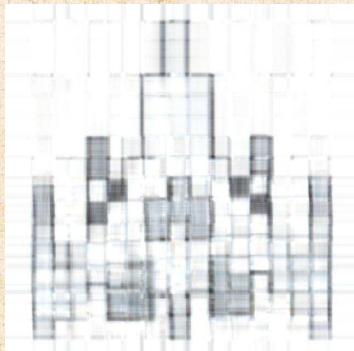
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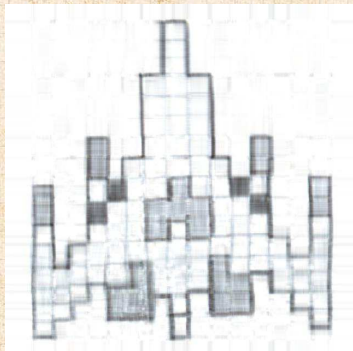
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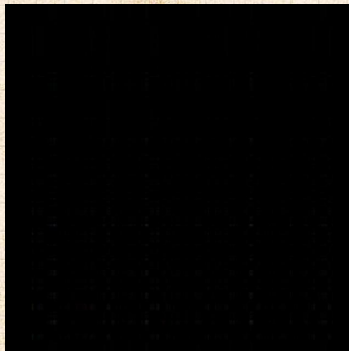
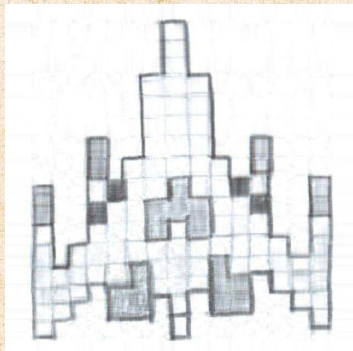
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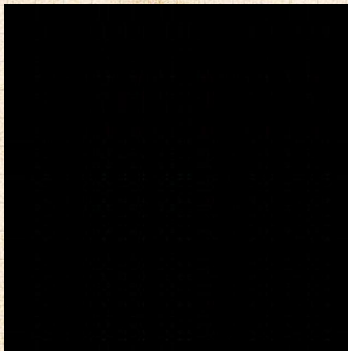
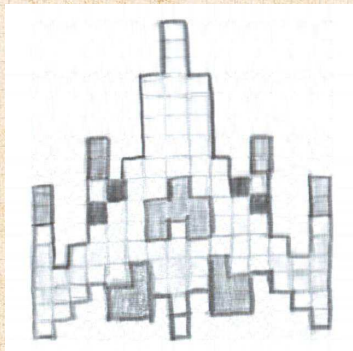
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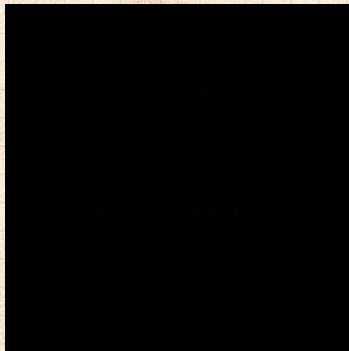
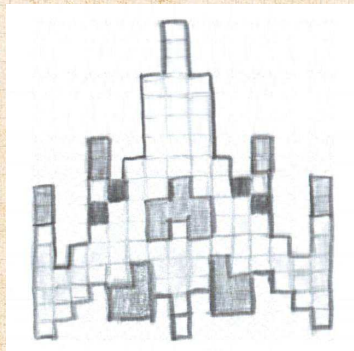
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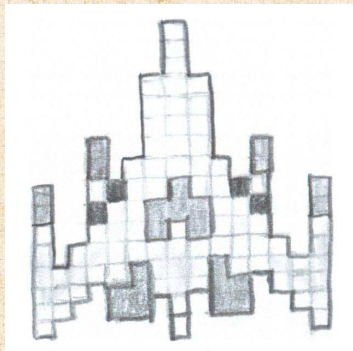
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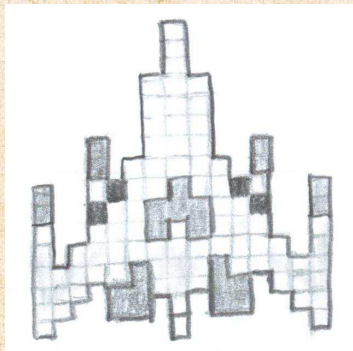
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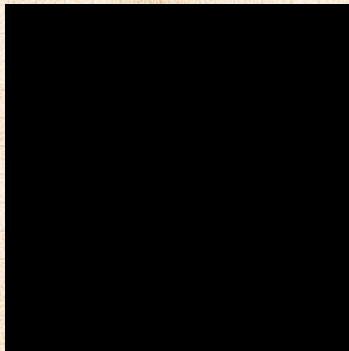
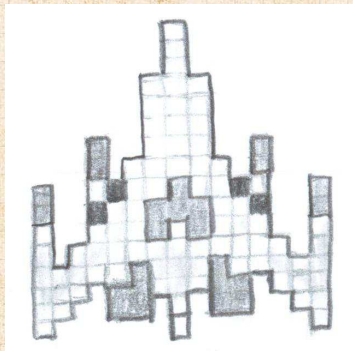
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^{560} \sigma_i \hat{u}_i \hat{v}_i^T$$

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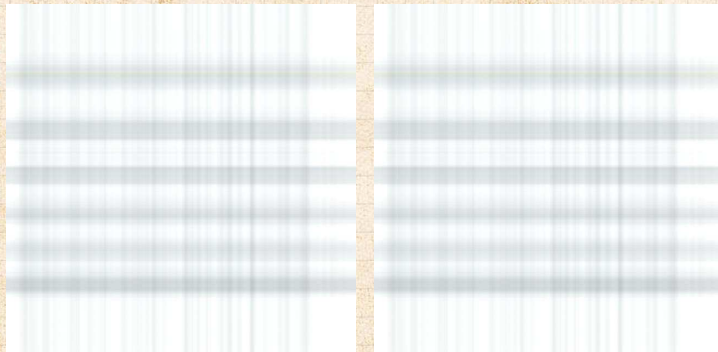
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^1 \sigma_i \hat{u}_i \hat{v}_i^T$$

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Linear Algebra

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Episode 25/25:

Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^2 \sigma_i \hat{u}_i \hat{v}_i^T$$

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Theorem of
Linear Algebra

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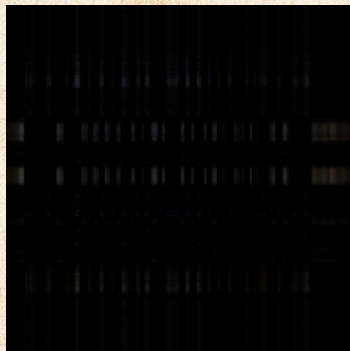
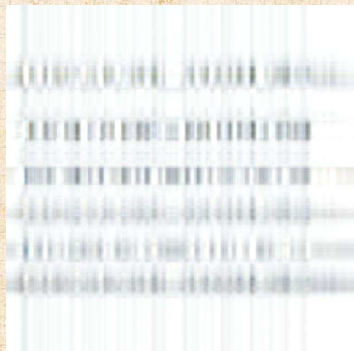
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^3 \sigma_i \hat{u}_i \hat{v}_i^T$$

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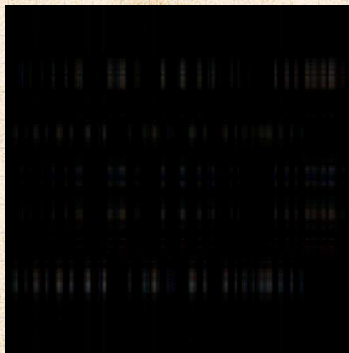
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^4 \sigma_i \hat{u}_i \hat{v}_i^T$$

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Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^5 \sigma_i \hat{u}_i \hat{v}_i^T$$

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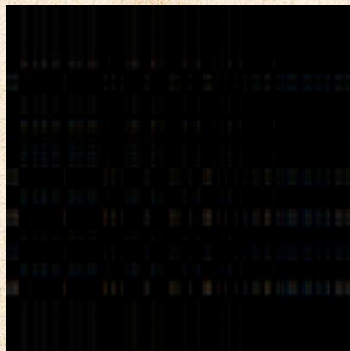
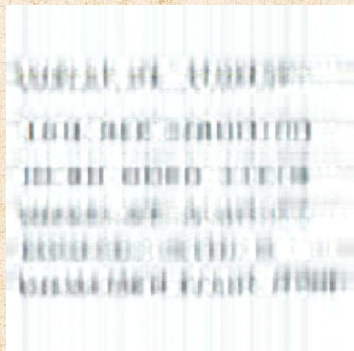
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^6 \sigma_i \hat{u}_i \hat{v}_i^T$$

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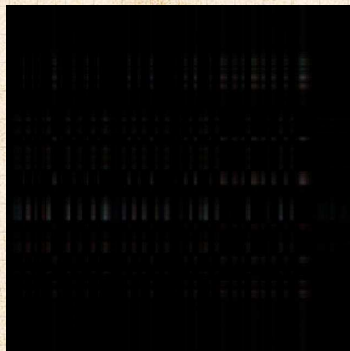
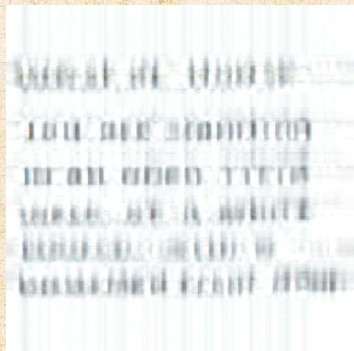
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^7 \sigma_i \hat{u}_i \hat{v}_i^T$$

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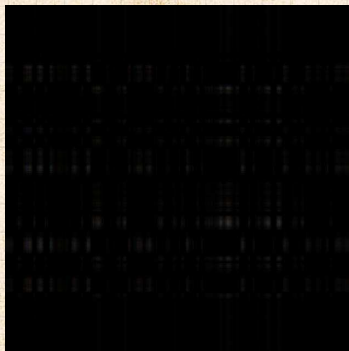
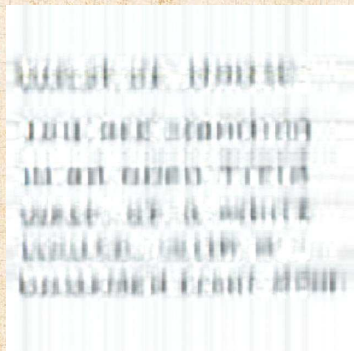
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^8 \sigma_i \hat{u}_i \hat{v}_i^T$$

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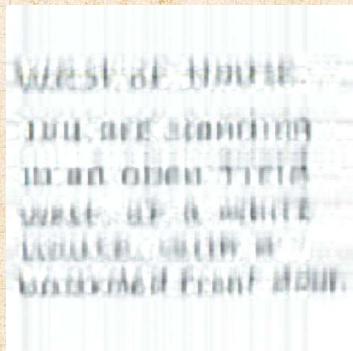
Singular Value
Decomposition

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$$\mathbf{A} = \sum_{i=1}^9 \sigma_i \hat{u}_i \hat{v}_i^T$$



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Image approximation (640 x 640)

Episode 25/25:

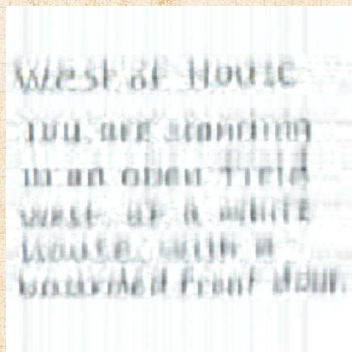
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^{10} \sigma_i \hat{u}_i \hat{v}_i^T$$

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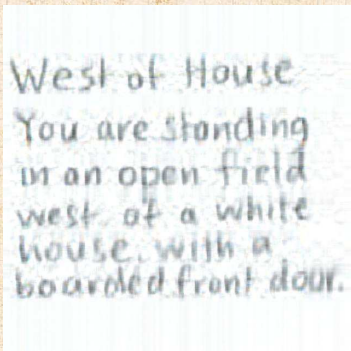
Singular Value
Decomposition

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Episode 25/25:

Singular Value
Decomposition

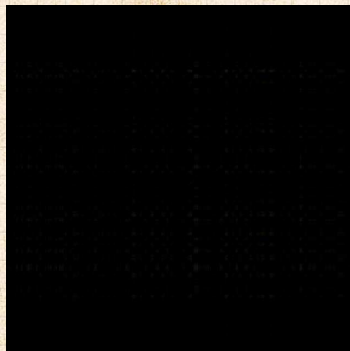
$$\mathbf{A} = \sum_{i=1}^{30} \sigma_i \hat{u}_i \hat{v}_i^T$$

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West of House
You are standing
in an open field
west of a white
house, with a
boarded front door.



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Image approximation (640 x 640)

Episode 25/25:

Singular Value
Decomposition

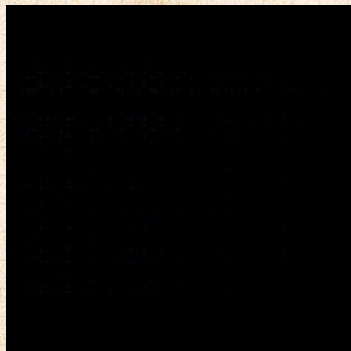
$$\mathbf{A} = \sum_{i=1}^{40} \sigma_i \hat{u}_i \hat{v}_i^T$$

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Image approximation (640 x 640)

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Singular Value
Decomposition

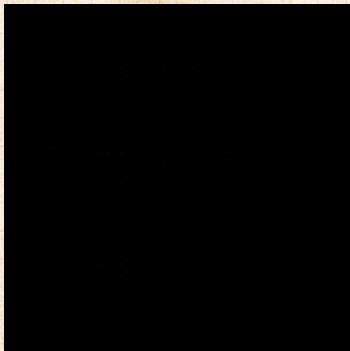
$$\mathbf{A} = \sum_{i=1}^{50} \sigma_i \hat{u}_i \hat{v}_i^T$$

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You are standing
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boarded front door.



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Image approximation (640 x 640)

Episode 25/25:

Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^{100} \sigma_i \hat{u}_i \hat{v}_i^T$$

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You are standing
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Image approximation (640 x 640)

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Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^{300} \sigma_i \hat{u}_i \hat{v}_i^T$$

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Image approximation (640 x 640)

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Singular Value
Decomposition

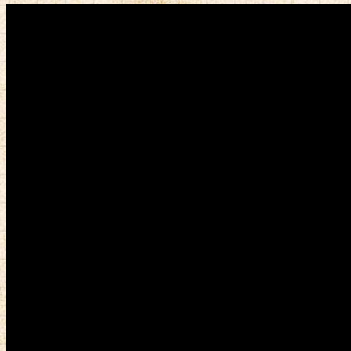
$$\mathbf{A} = \sum_{i=1}^{640} \sigma_i \hat{u}_i \hat{v}_i^T$$

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Image approximation (640 x 640)

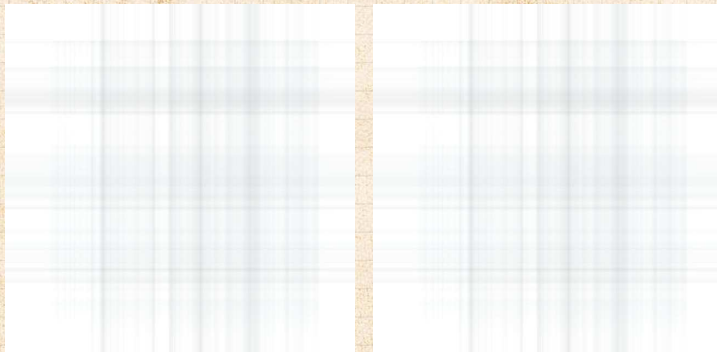
Episode 25/25:
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^1 \sigma_i \hat{u}_i \hat{v}_i^T$$

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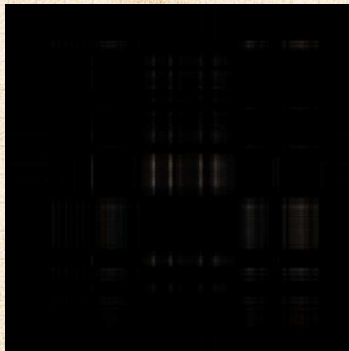
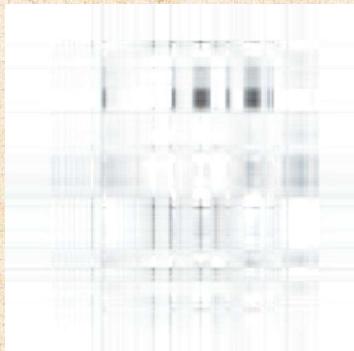
Singular Value
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$$\mathbf{A} = \sum_{i=1}^4 \sigma_i \hat{u}_i \hat{v}_i^T$$

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$$\mathbf{A} = \sum_{i=1}^5 \sigma_i \hat{u}_i \hat{v}_i^T$$

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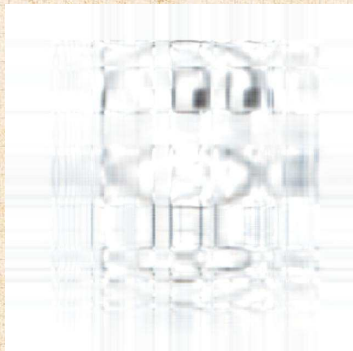
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^6 \sigma_i \hat{u}_i \hat{v}_i^T$$

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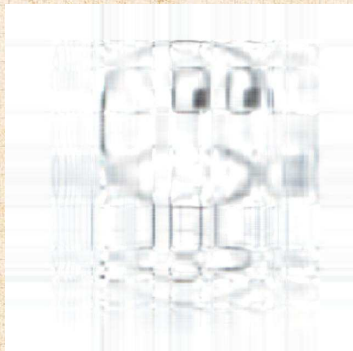
Episode 25/25:
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$$\mathbf{A} = \sum_{i=1}^7 \sigma_i \hat{u}_i \hat{v}_i^T$$



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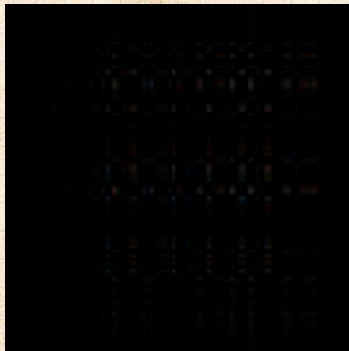
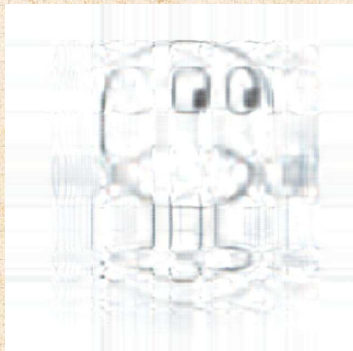
Episode 25/25:
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^8 \sigma_i \hat{u}_i \hat{v}_i^T$$

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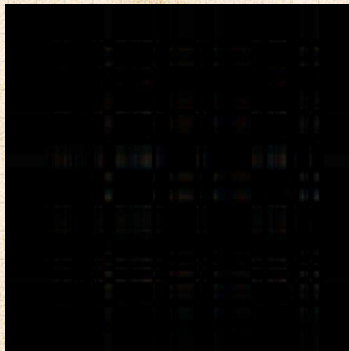
Singular Value
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$$\mathbf{A} = \sum_{i=1}^9 \sigma_i \hat{u}_i \hat{v}_i^T$$

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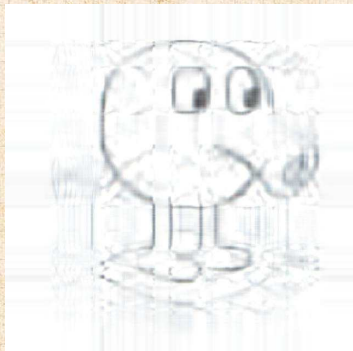
Episode 25/25:
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^{10} \sigma_i \hat{u}_i \hat{v}_i^T$$

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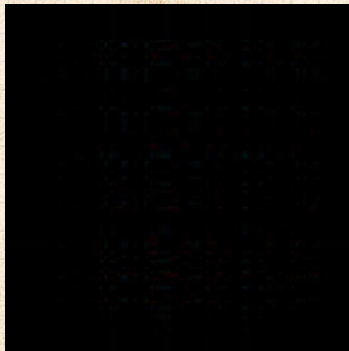
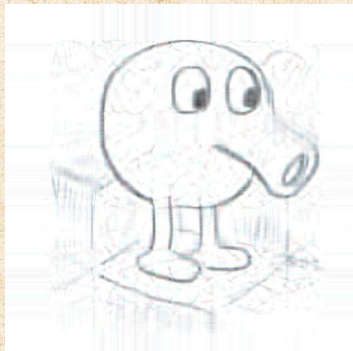
Singular Value
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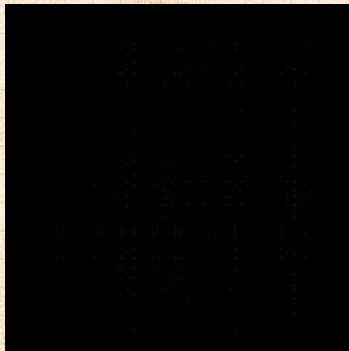
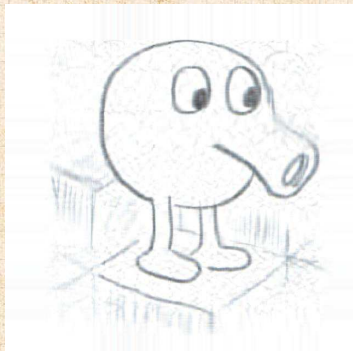
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^{30} \sigma_i \hat{u}_i \hat{v}_i^T$$

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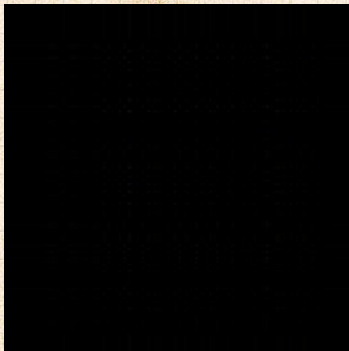
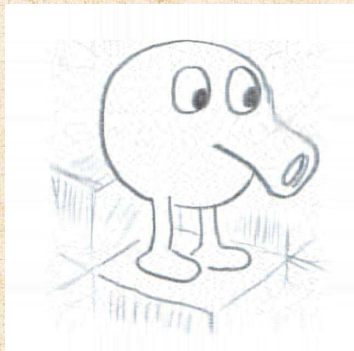
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^{40} \sigma_i \hat{u}_i \hat{v}_i^T$$

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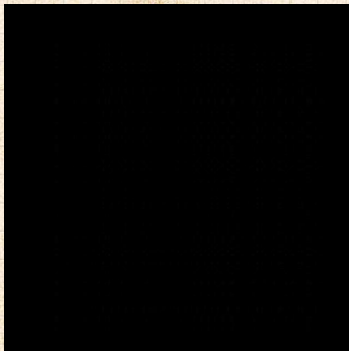
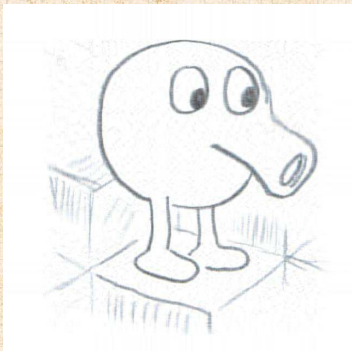
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^{50} \sigma_i \hat{u}_i \hat{v}_i^T$$

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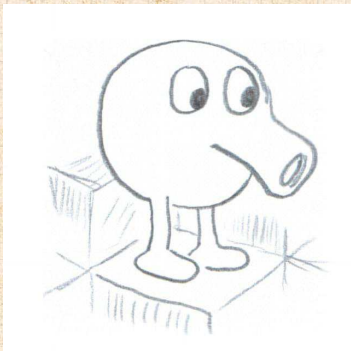
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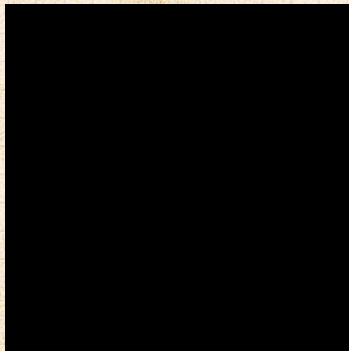
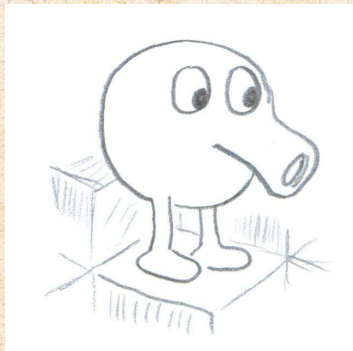
Episode 25/25:
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^{300} \sigma_i \hat{u}_i \hat{v}_i^T$$

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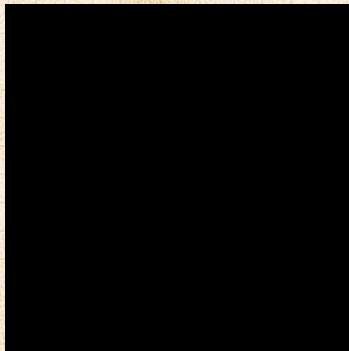
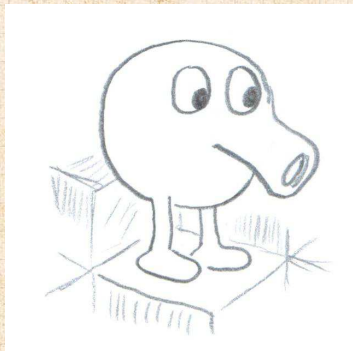
Episode 25/25:
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^{540} \sigma_i \hat{u}_i \hat{v}_i^T$$

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Decomposition

$$\mathbf{A} = \sum_{i=1}^1 \sigma_i \hat{u}_i \hat{v}_i^T$$

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Episode 25/25:
Singular Value
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$$\mathbf{A} = \sum_{i=1}^2 \sigma_i \hat{u}_i \hat{v}_i^T$$

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Image approximation (262 x 248)

Episode 25/25:
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^3 \sigma_i \hat{u}_i \hat{v}_i^T$$

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Image approximation (262 x 248)

Episode 25/25:
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^4 \sigma_i \hat{u}_i \hat{v}_i^T$$

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Episode 25/25:
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^5 \sigma_i \hat{u}_i \hat{v}_i^T$$

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Episode 25/25:

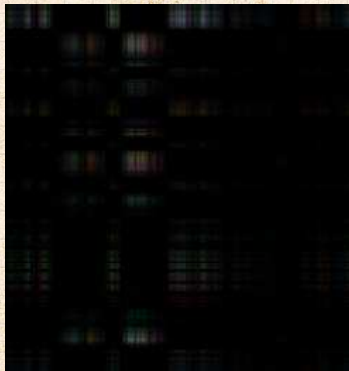
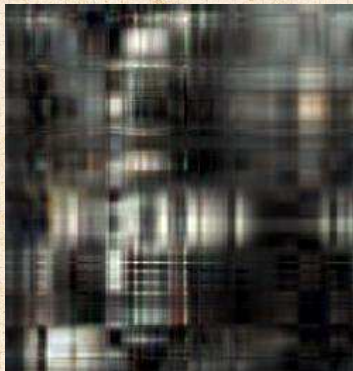
Singular Value
Decomposition

$$\mathbf{A} = \sum_{i=1}^6 \sigma_i \hat{u}_i \hat{v}_i^T$$

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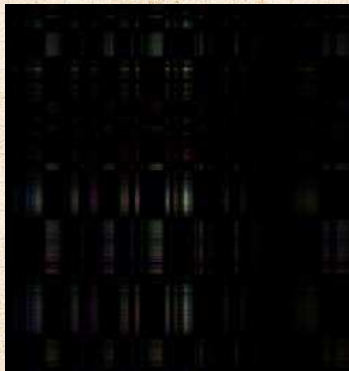
Episode 25/25:
Singular Value
Decomposition

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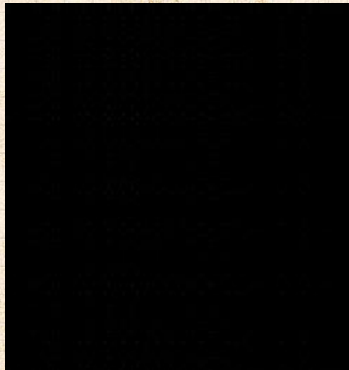
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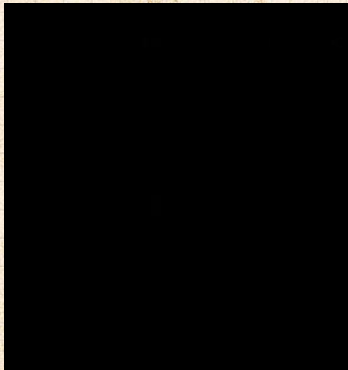


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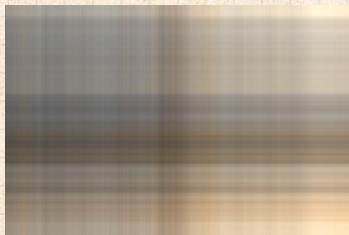
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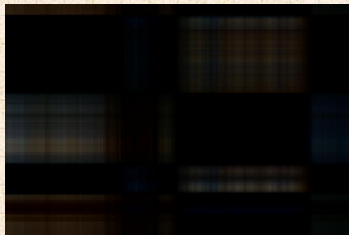
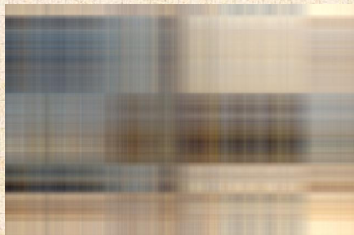
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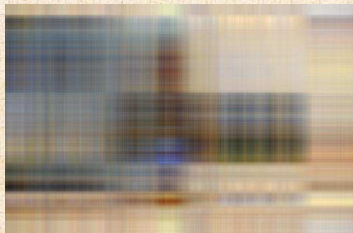
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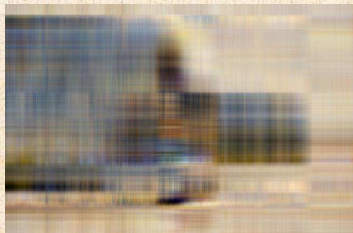
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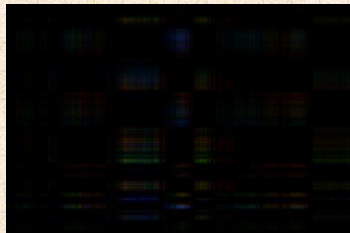
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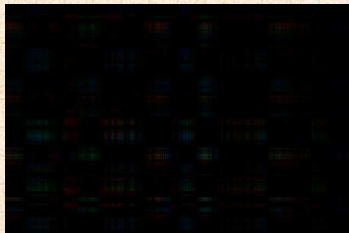
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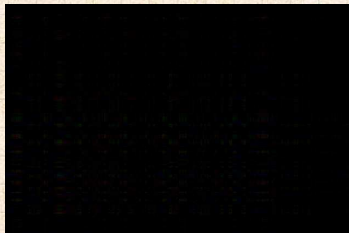
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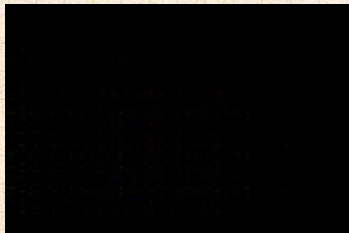
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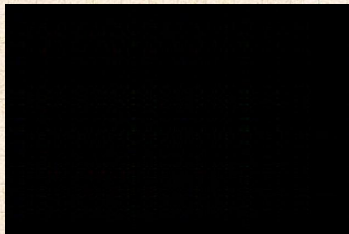
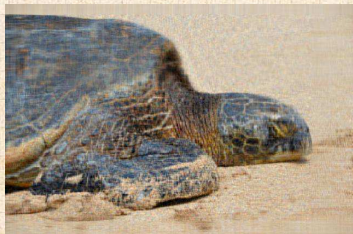
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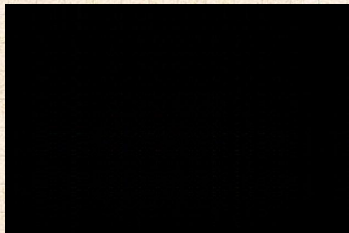
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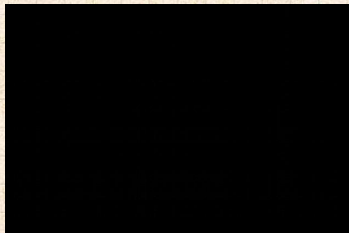
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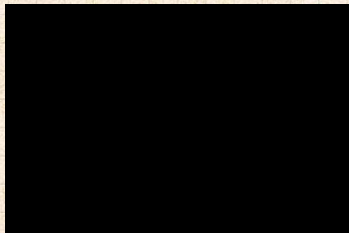
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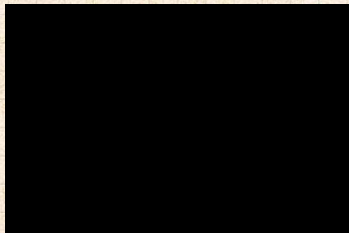
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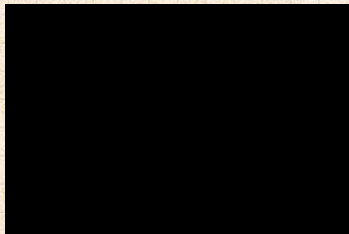
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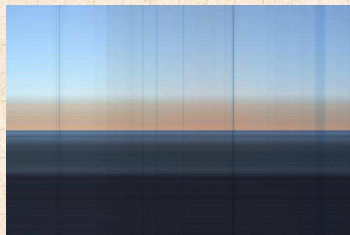
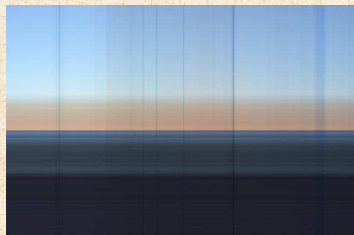
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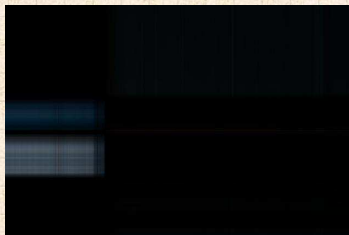
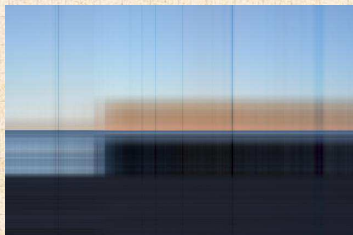
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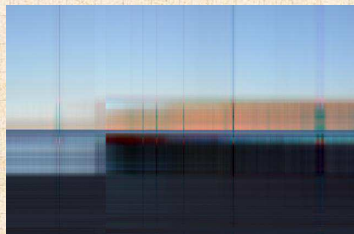
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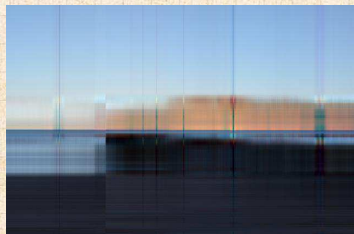
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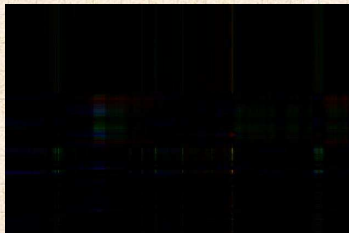
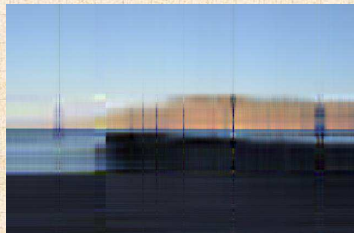
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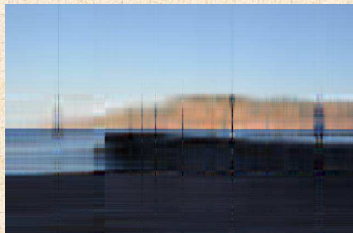
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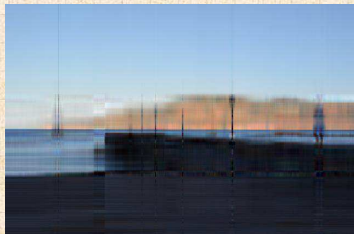
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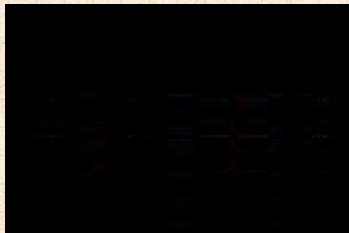
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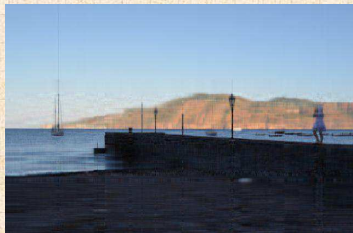
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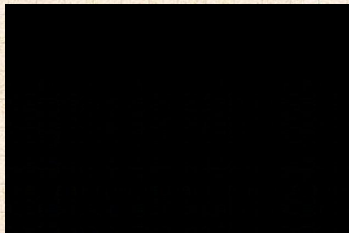
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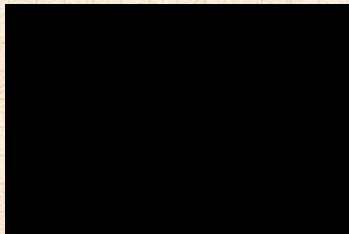
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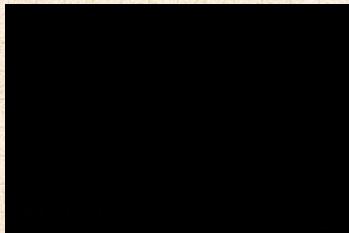
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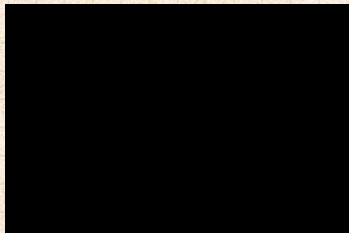
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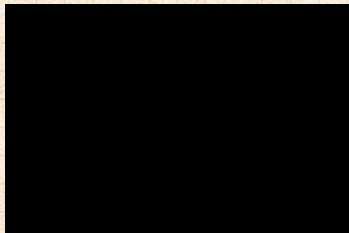
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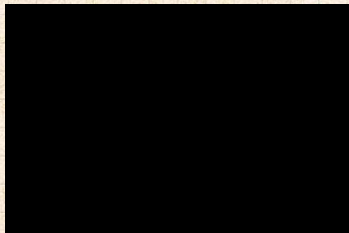
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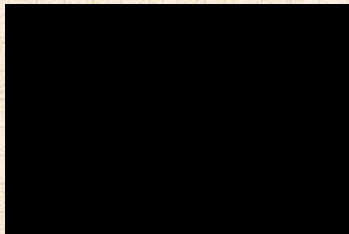
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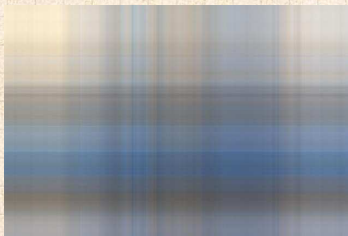
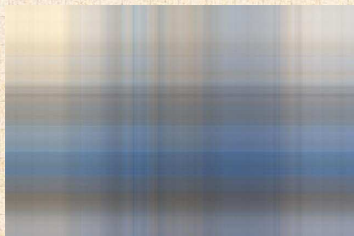
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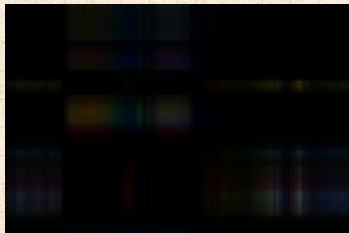
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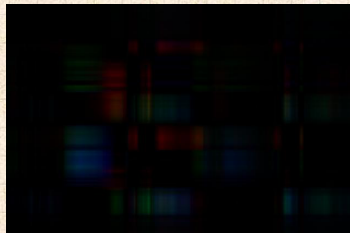
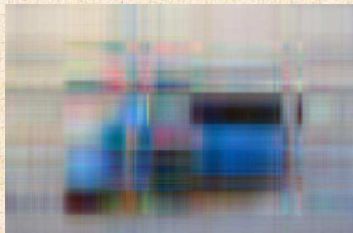
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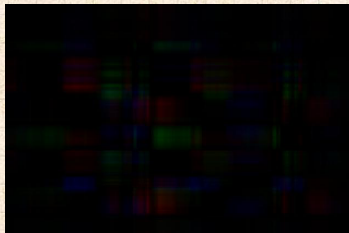
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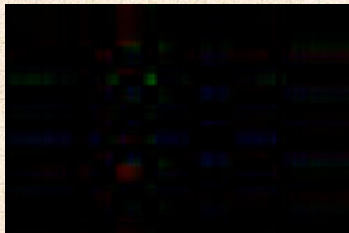
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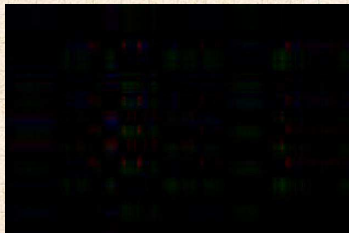
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$$\mathbf{A} = \sum_{i=1}^9 \sigma_i \hat{u}_i \hat{v}_i^T$$



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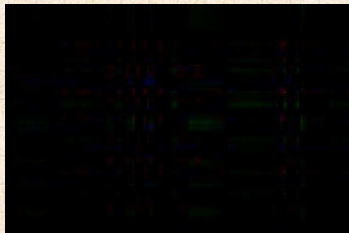
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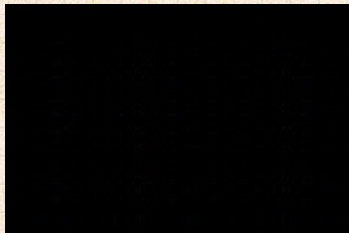
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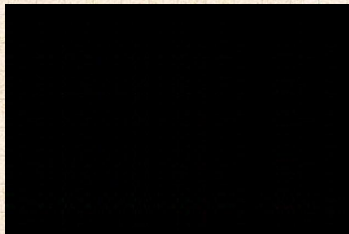
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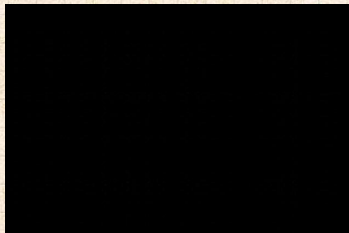
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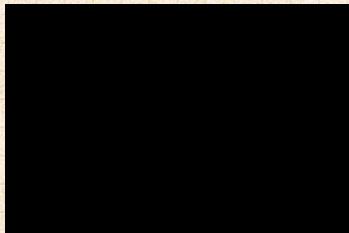
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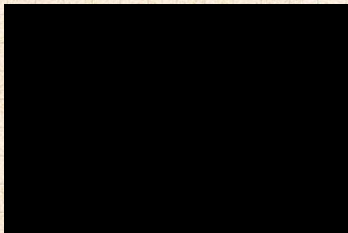
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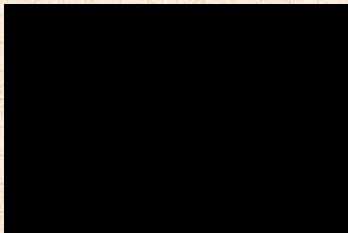
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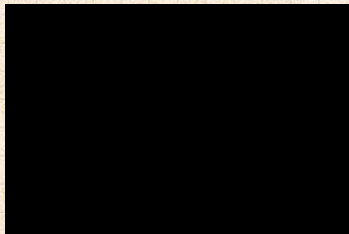
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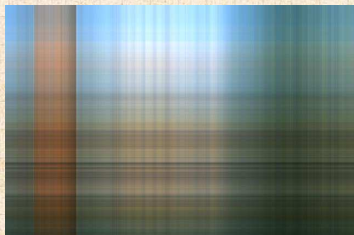
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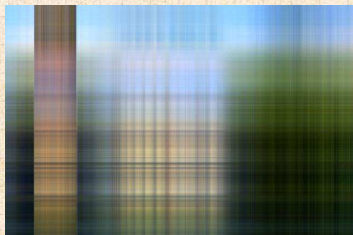
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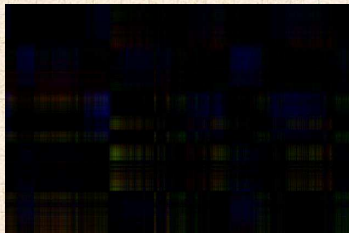
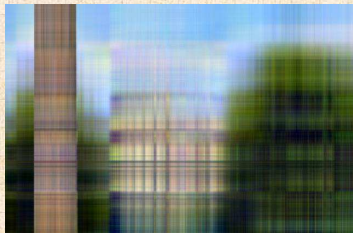
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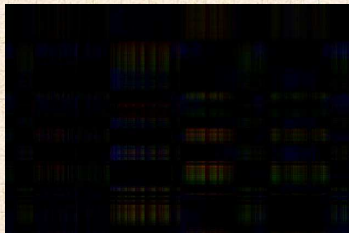
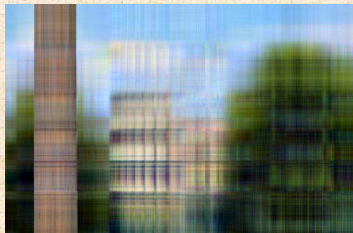
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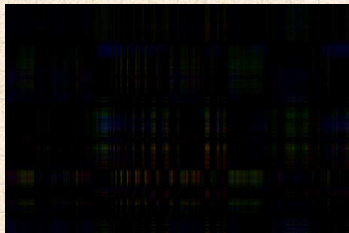
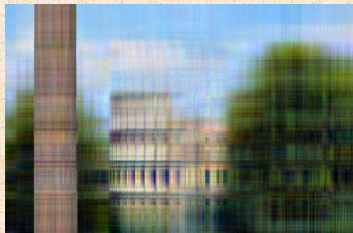
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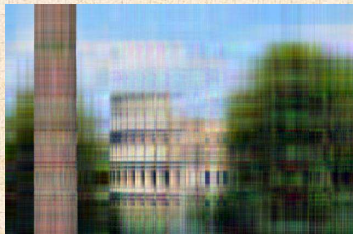
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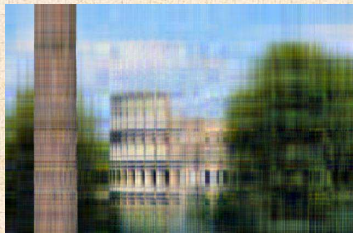
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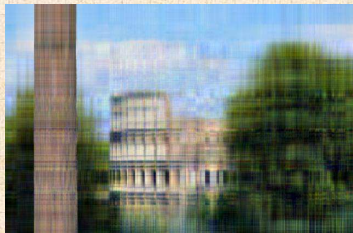
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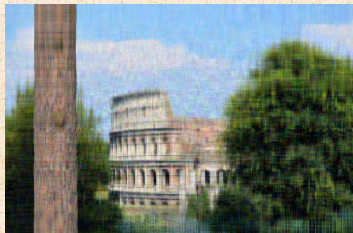
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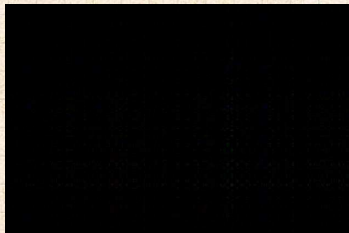
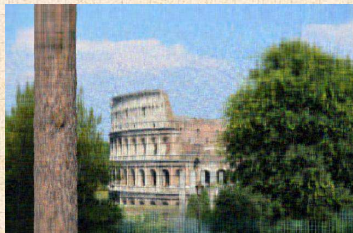
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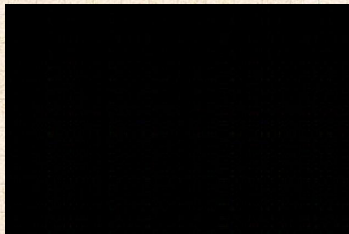
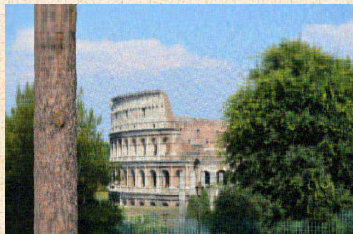
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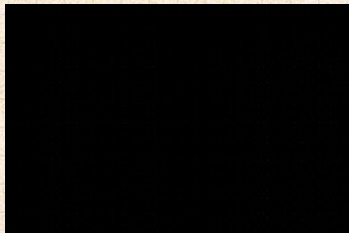
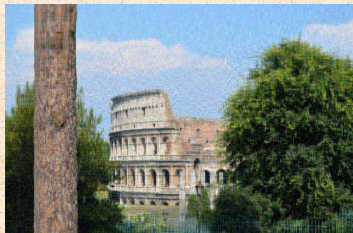
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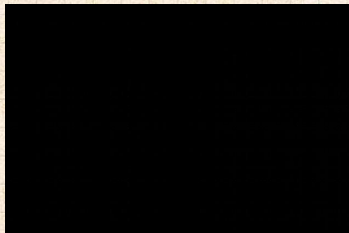
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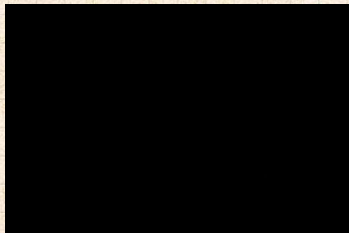
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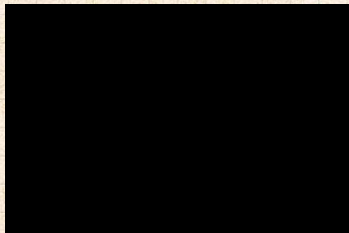
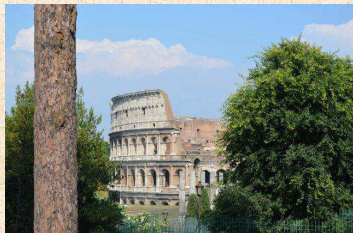
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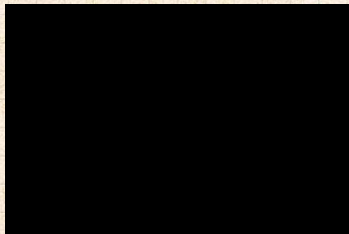
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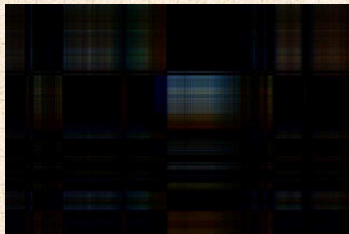
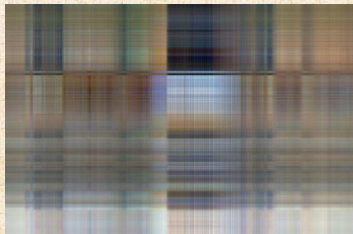
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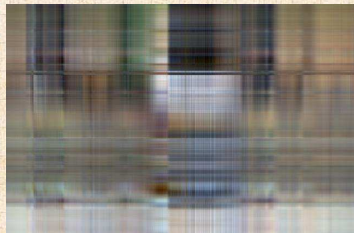
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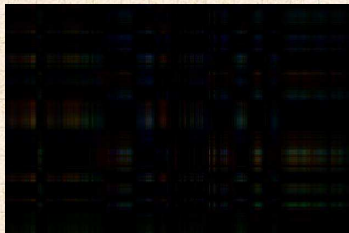
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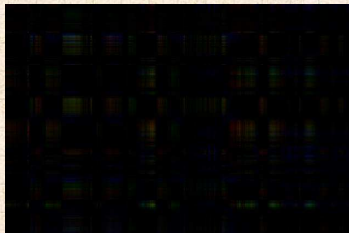
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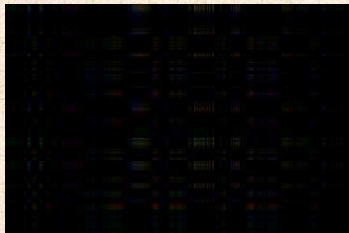
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$$\mathbf{A} = \sum_{i=1}^{10} \sigma_i \hat{u}_i \hat{v}_i^T$$



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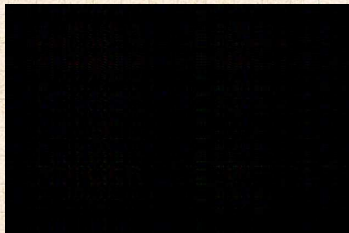
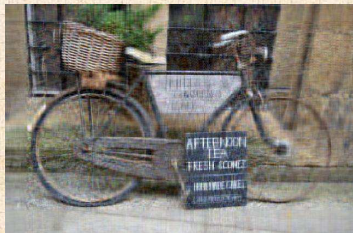
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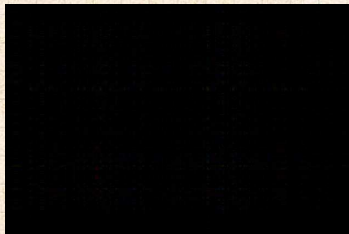
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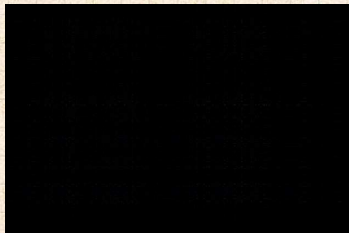
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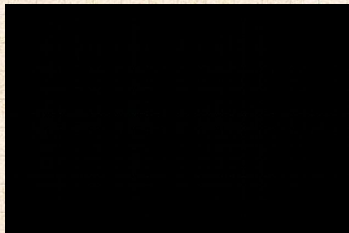
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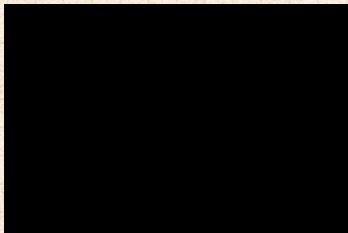
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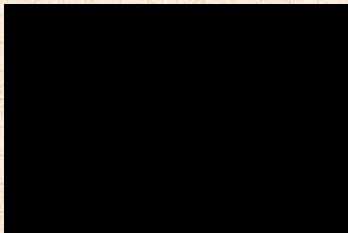
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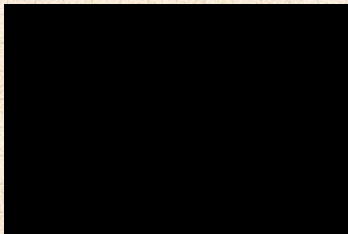
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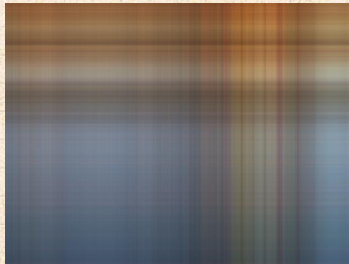
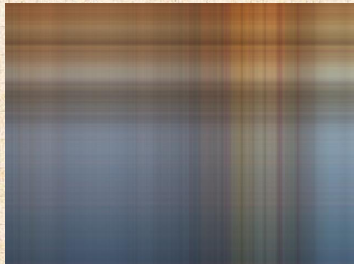
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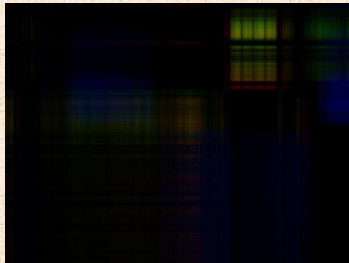
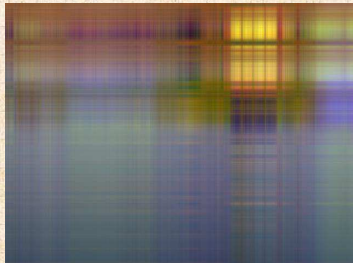
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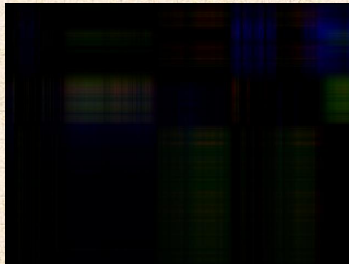
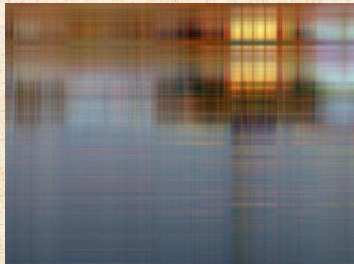
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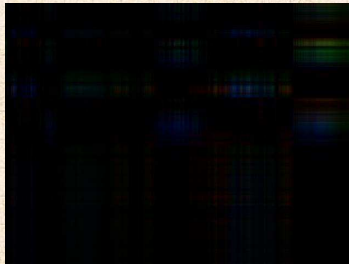
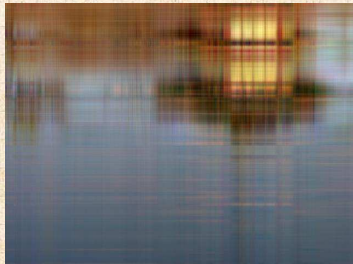
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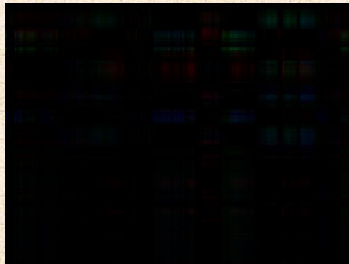
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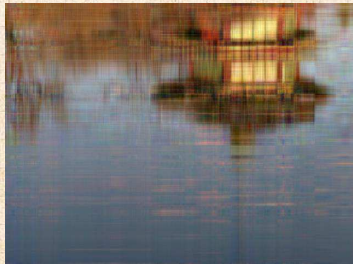
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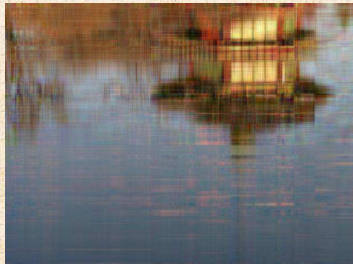
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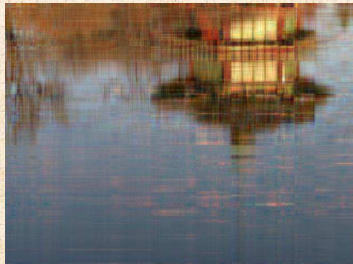
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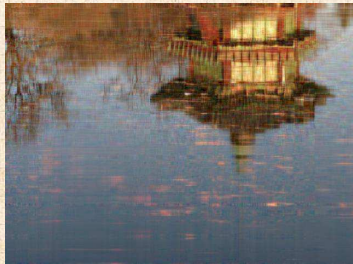
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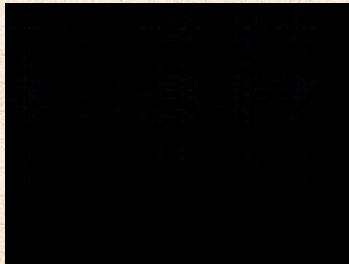
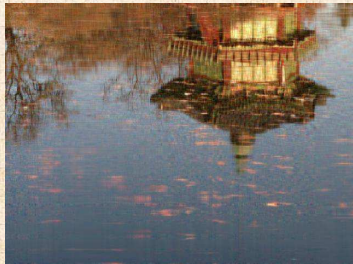
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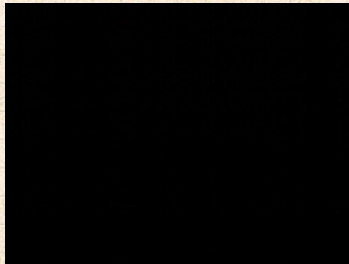
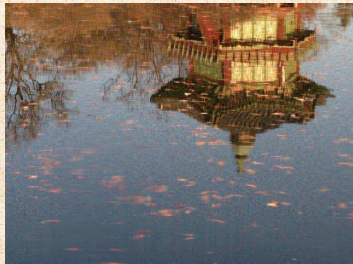
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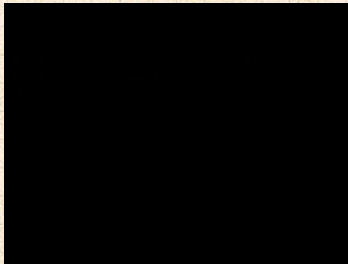
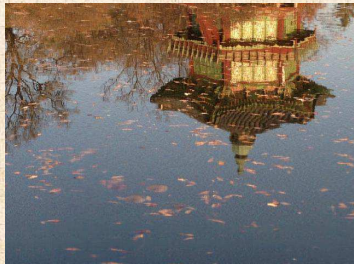
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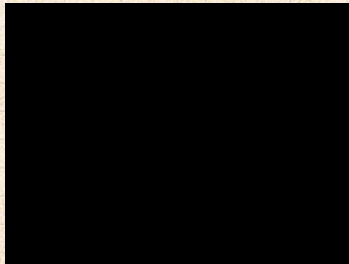
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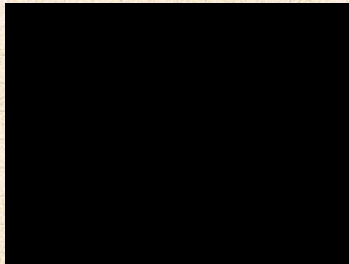
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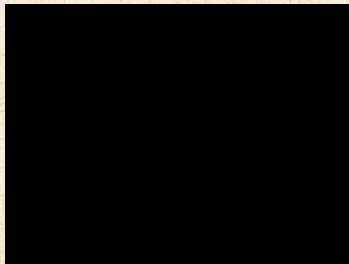
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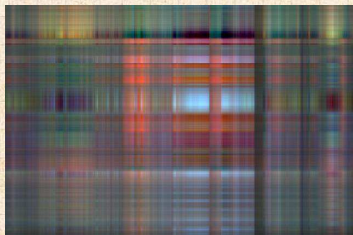
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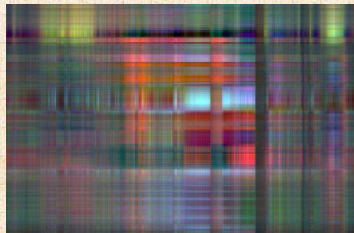
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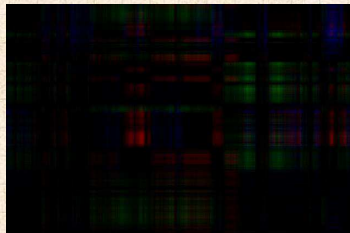
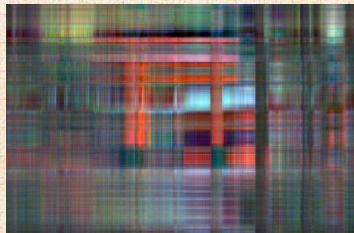
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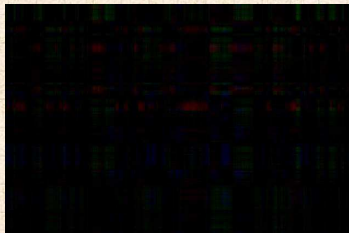
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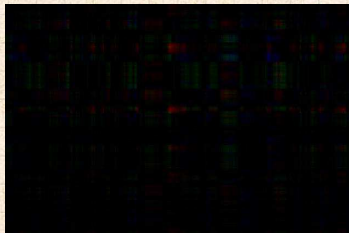
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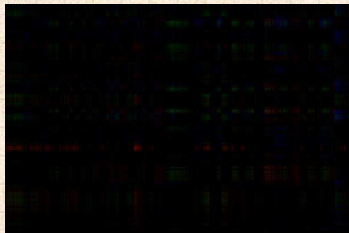
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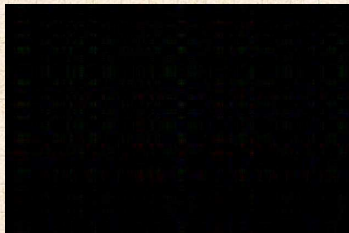
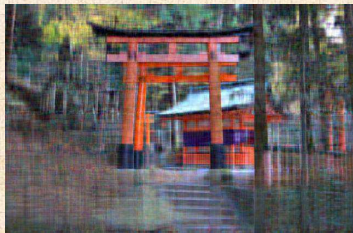
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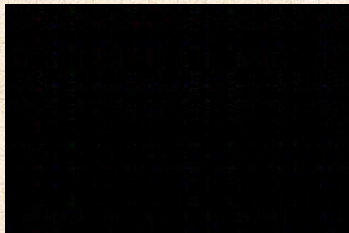
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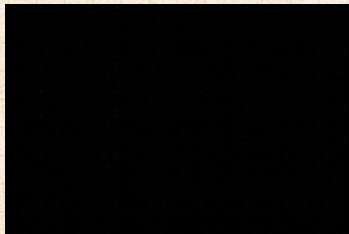
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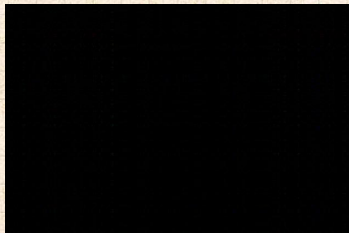
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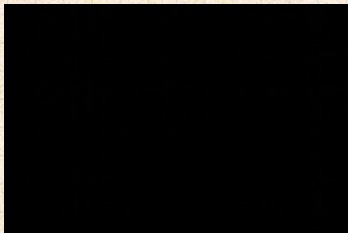
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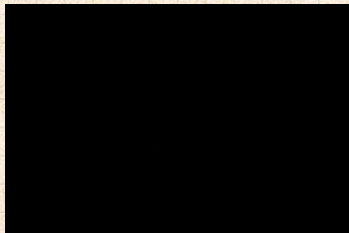
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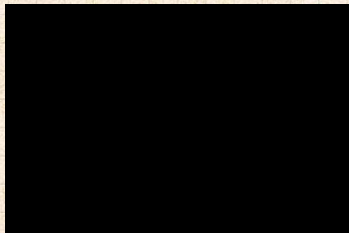
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$$\mathbf{A} = \sum_{i=1}^{300} \sigma_i \hat{u}_i \hat{v}_i^T$$



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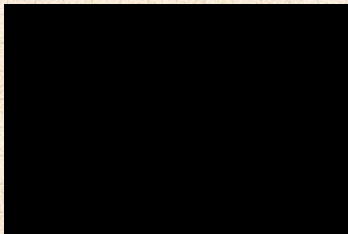
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$$\mathbf{A} = \sum_{i=1}^{420} \sigma_i \hat{u}_i \hat{v}_i^T$$



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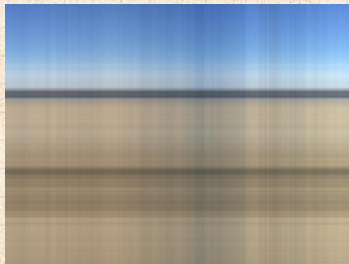
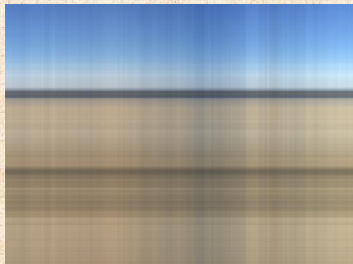
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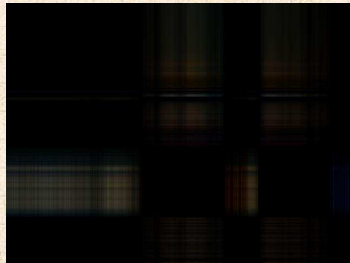
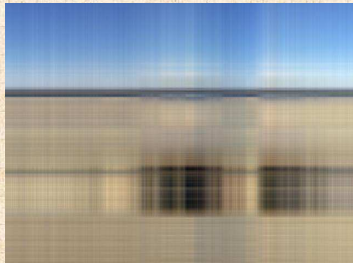
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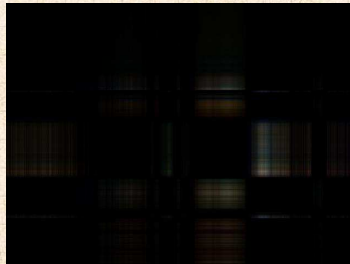
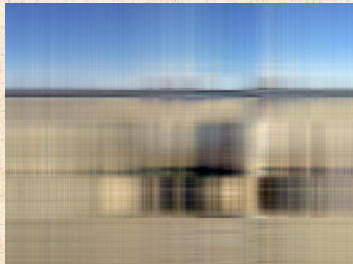
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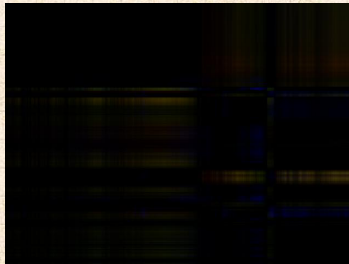
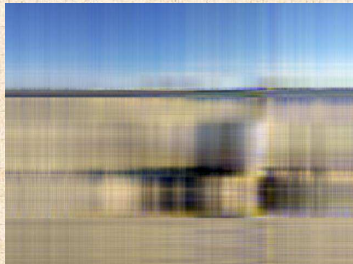
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$$\mathbf{A} = \sum_{i=1}^4 \sigma_i \hat{u}_i \hat{v}_i^T$$



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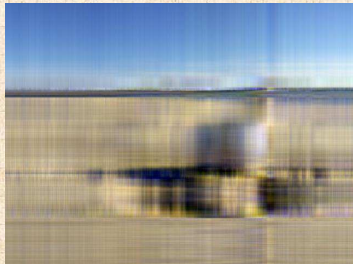
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$$\mathbf{A} = \sum_{i=1}^5 \sigma_i \hat{u}_i \hat{v}_i^T$$



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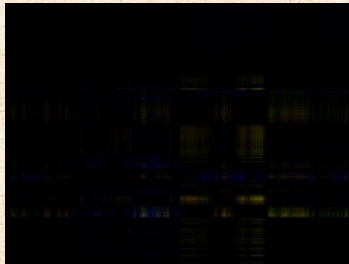
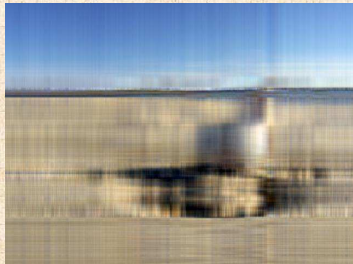
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$$\mathbf{A} = \sum_{i=1}^7 \sigma_i \hat{u}_i \hat{v}_i^T$$



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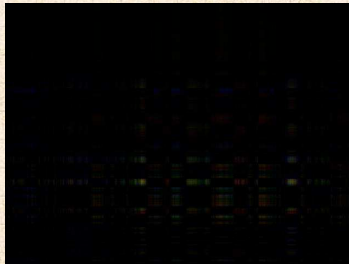
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$$\mathbf{A} = \sum_{i=1}^8 \sigma_i \hat{u}_i \hat{v}_i^T$$



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$$\mathbf{A} = \sum_{i=1}^9 \sigma_i \hat{u}_i \hat{v}_i^T$$



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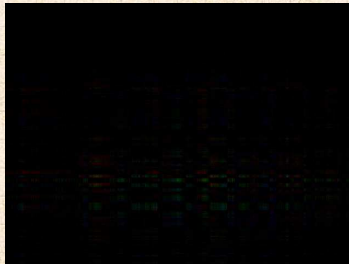
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$$\mathbf{A} = \sum_{i=1}^{10} \sigma_i \hat{u}_i \hat{v}_i^T$$



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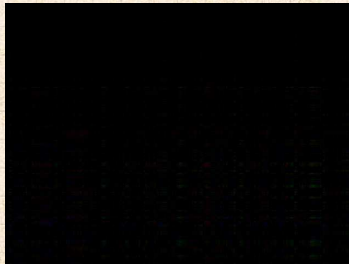
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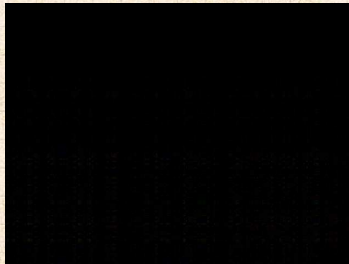
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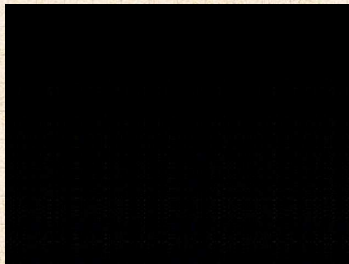
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$$\mathbf{A} = \sum_{i=1}^{40} \sigma_i \hat{u}_i \hat{v}_i^T$$



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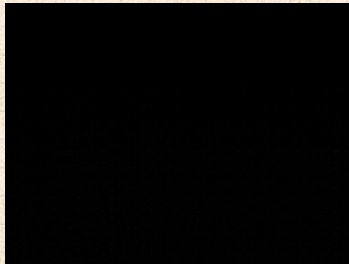
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$$\mathbf{A} = \sum_{i=1}^{50} \sigma_i \hat{u}_i \hat{v}_i^T$$



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$$\mathbf{A} = \sum_{i=1}^{100} \sigma_i \hat{u}_i \hat{v}_i^T$$



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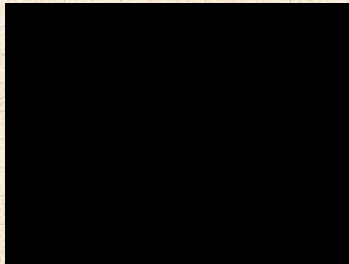
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$$\mathbf{A} = \sum_{i=1}^{200} \sigma_i \hat{u}_i \hat{v}_i^T$$



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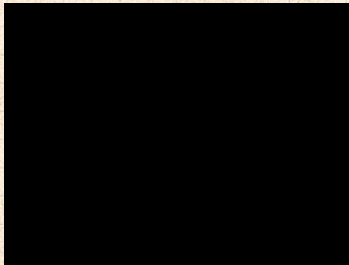
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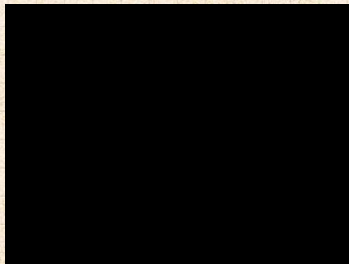
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$$\mathbf{A} = \sum_{i=1}^{480} \sigma_i \hat{u}_i \hat{v}_i^T$$



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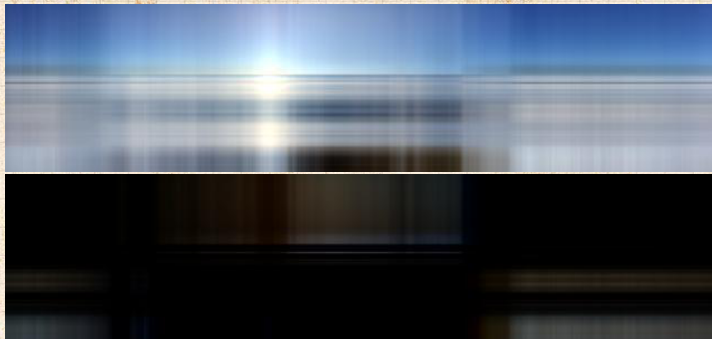
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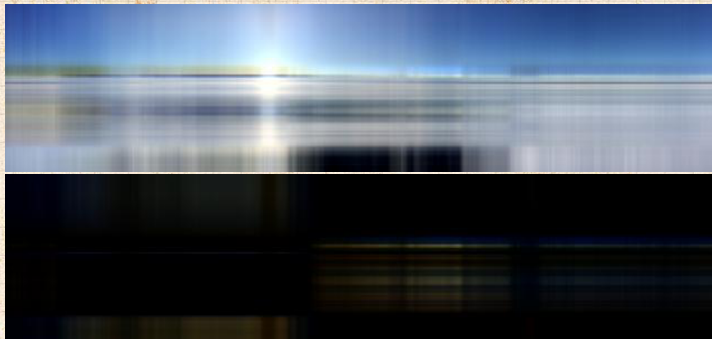
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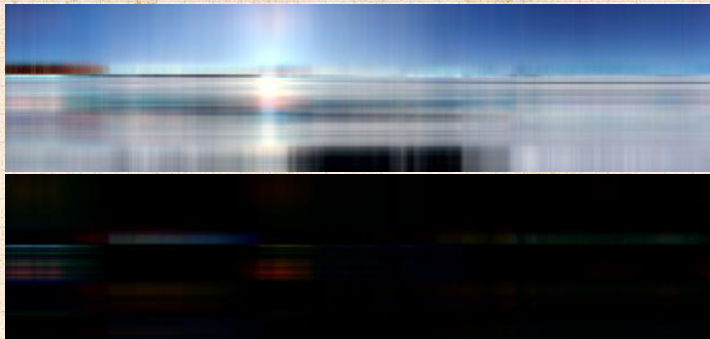
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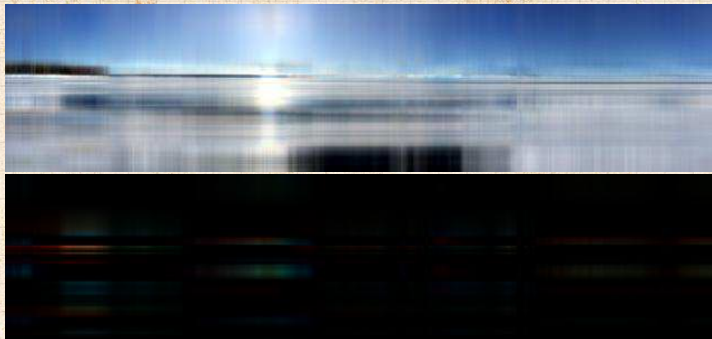
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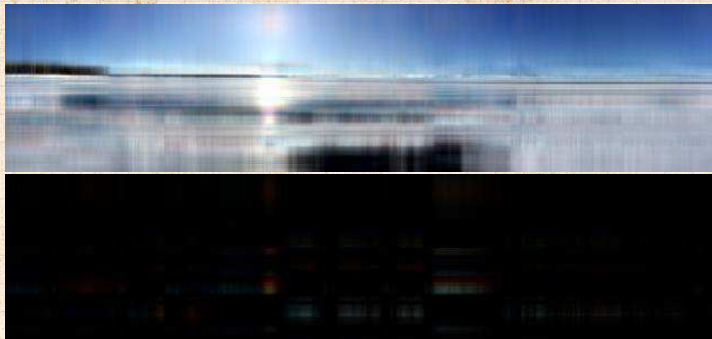
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$$\mathbf{A} = \sum_{i=1}^6 \sigma_i \hat{u}_i \hat{v}_i^T$$

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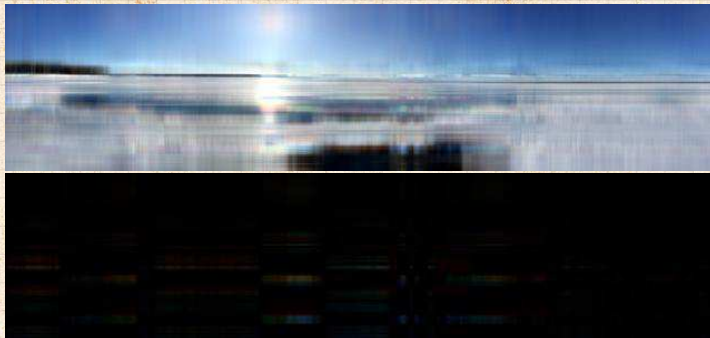
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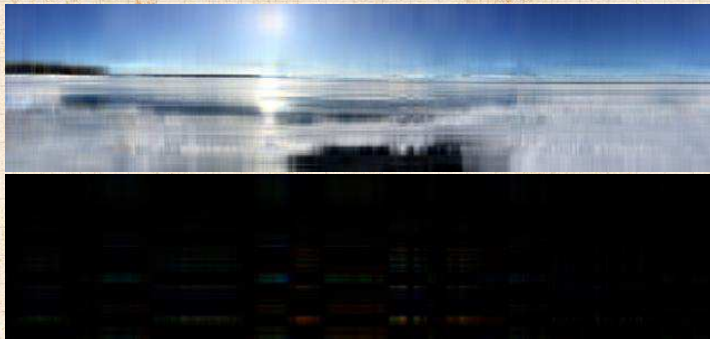
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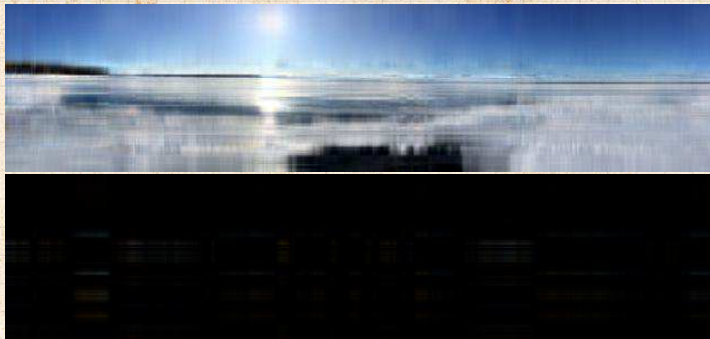
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$$\mathbf{A} = \sum_{i=1}^{150} \sigma_i \hat{u}_i \hat{v}_i^T$$



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