Computer Vision for Visual Effects

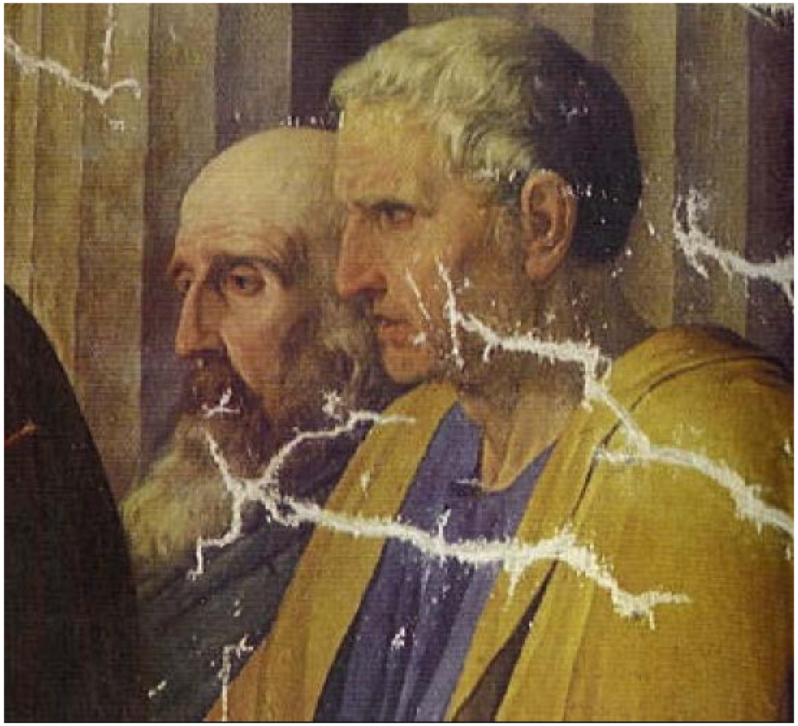
CVFX 2015

Today's Plan

- *Object Removal by Exemplar-Based Inpainting*
  - Criminisi *et al.*
  - CVPR 2003

- *Online Dictionary Learning for Sparse Coding*
  - Mairal *et al.*
  - ICML 2009

Inpainting



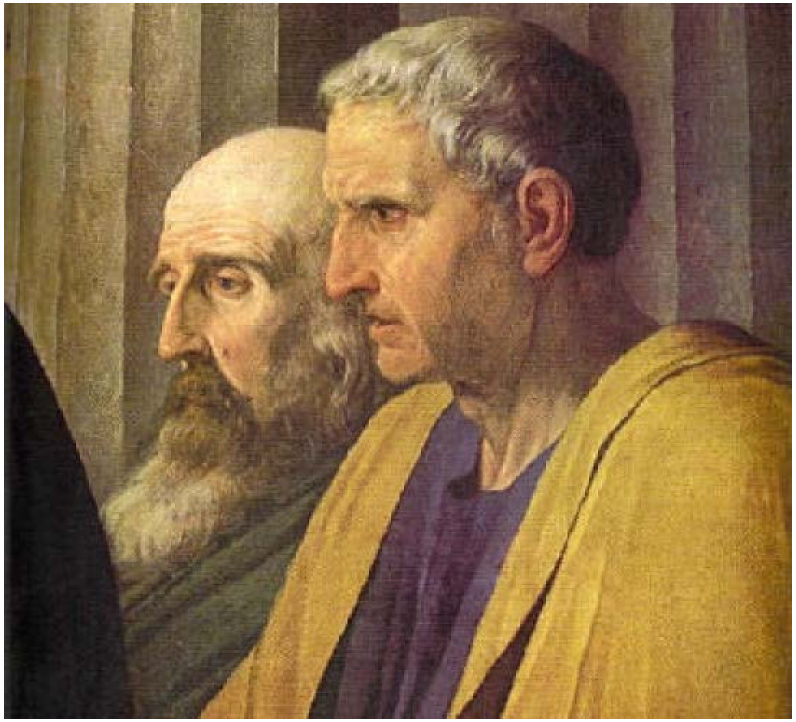


Photo Restoration

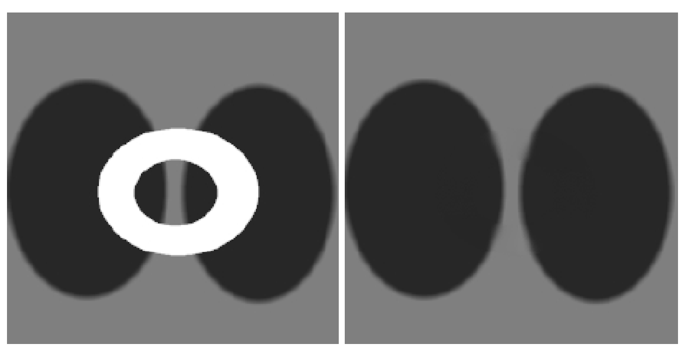
Object Removal

Automatic Digital Inpainting

[Bertalmio *et al.]*

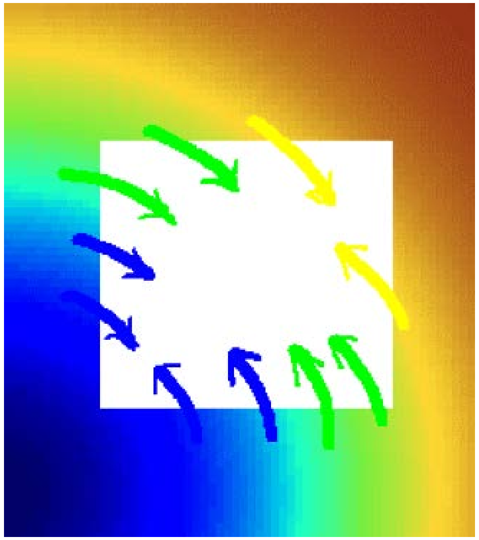
Automatic Digital Inpainting

[Bertalmio *et al.]*



The Algorithm of Bertalmio *et al.*

- Imitating professionals
- Propagation of information
  - Smoothness



isophotes: lines of equal gray values

$$\nabla(\text{Smoothness}) \cdot \nabla^{\perp} I = 0$$

(Laplacian)

$$\frac{\partial I}{\partial t} = \nabla(fI) \cdot \nabla^{\perp} I$$

introduces blur in large regions

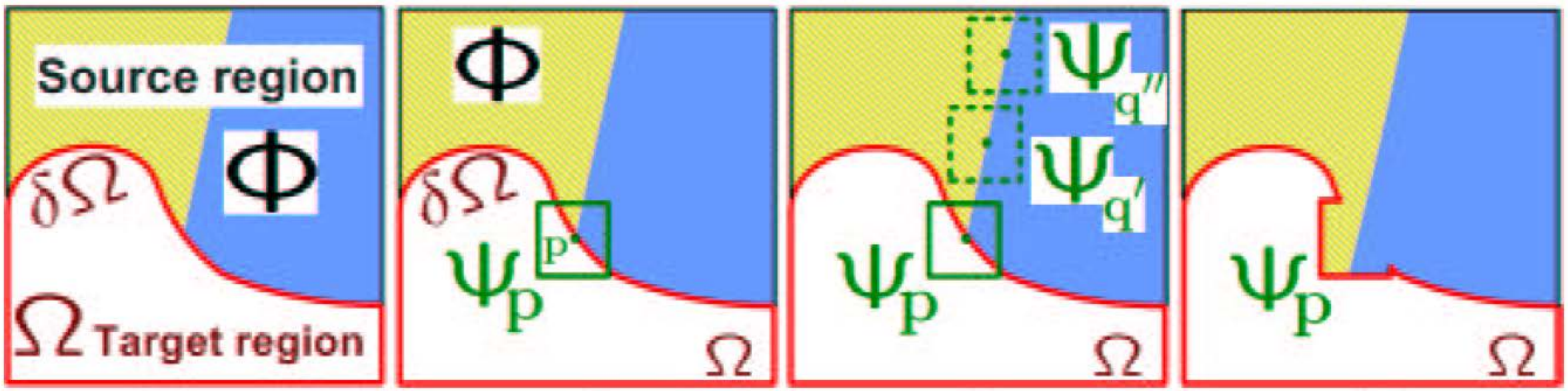
$$I^{n+1}(i,j) = I^{n}(i,j) + \Delta t I_t^n(i,j), \forall (i,j) \in \Omega$$

Exemplar-Based Texture Synthesis

- To replicate both texture and structure
  - Special attention to linear structures
  - Dependent on the order in which the filling proceeds
  - Propagation of confidence

Isophote-Driven Image Sampling

- Find the best-match source patch
- Isophote orientation is automatically preserved



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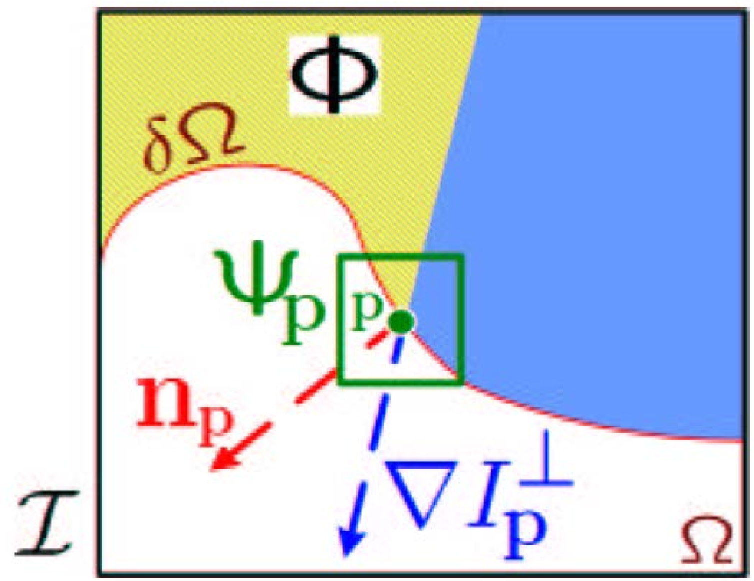
Region-Filling Algorithm

- Window size: 9x9 pixels
  - Greater than the largest texel or the thickest structure



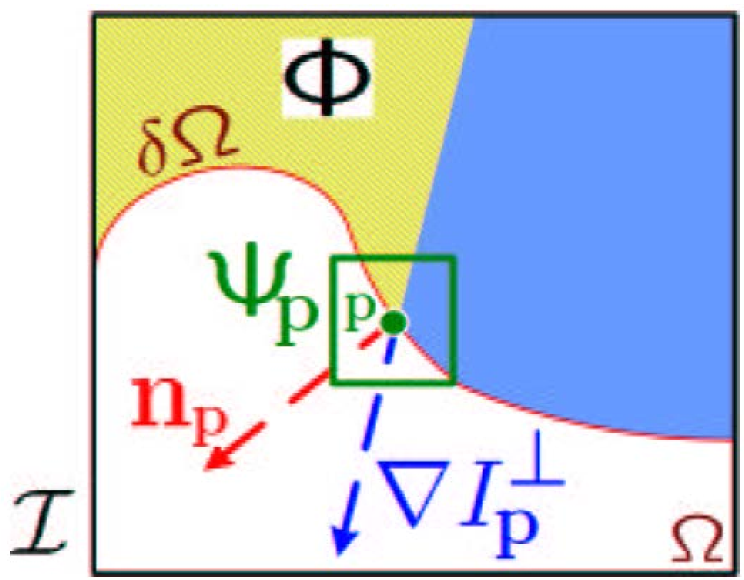
- Encouraging propagation of linear structure together with texture

Computing Patch Priorities

- Best-first
  - Patches which are on the continuation of strong edges and which are surrounded by high-confidence pixels

$$P(\mathbf{p}) = C(\mathbf{p})D(\mathbf{p}) \quad \mathbf{p} \in \delta\Omega$$

priority = confidence term * data term



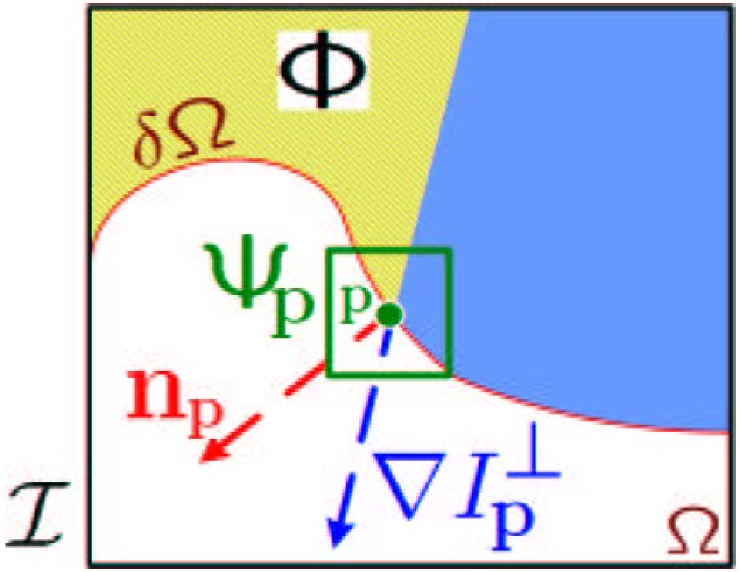
Confidence Term

$$C(\mathbf{p}) = \frac{\sum_{\mathbf{q} \in \Psi_{\mathbf{p}} \cap \bar{\Omega}} C(\mathbf{q})}{|\Psi_{\mathbf{p}}|}$$

amount of reliable information surrounding the pixel **p**

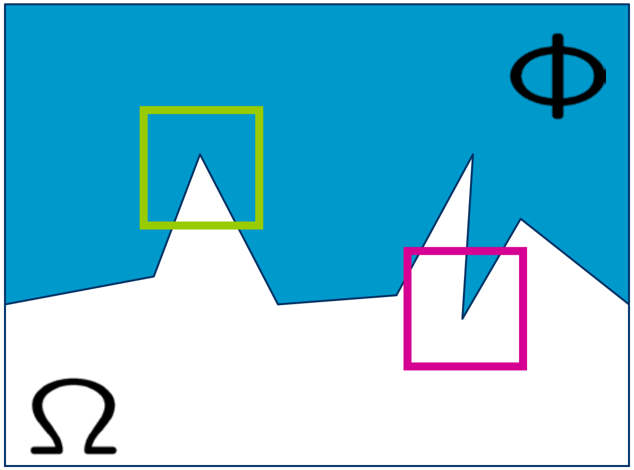
$\Psi_{\mathbf{p}}$: patch

$|\Psi_{\mathbf{p}}|$: area of $\Psi_{\mathbf{p}}$



Intuition

- "Patches that include corners and thin tendrils of the target region will tend to be filled first, as they are surrounded by more pixels from the original image. These patches provide more reliable information against which to match. Conversely, patches at the tip of 'peninsulas' of filled pixels jutting into the target region will tend to be set aside until more of the surrounding pixels are filled in."



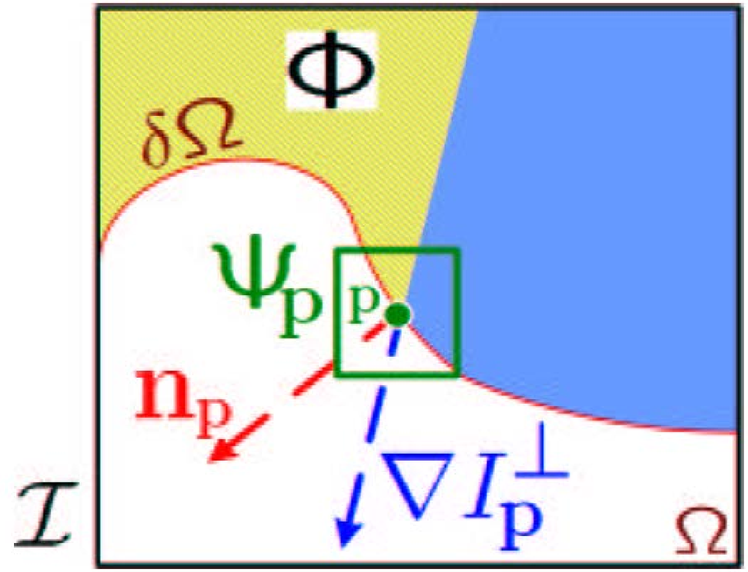
Data Term

$$D(\mathbf{p}) = \frac{|\nabla I_{\mathbf{p}}^{\perp} \cdot \mathbf{n}_{\mathbf{p}}|}{\alpha}$$

strength of isophotes
hitting the fror $\delta\Omega$

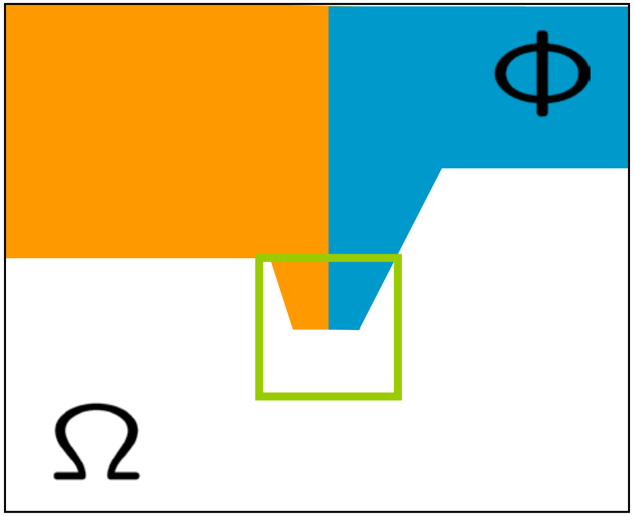
$\mathbf{n}_{\mathbf{p}}$: unit vector orthogonal to the front $\delta\Omega$

$\alpha = 255$



Balance between the Confidence and Data Terms

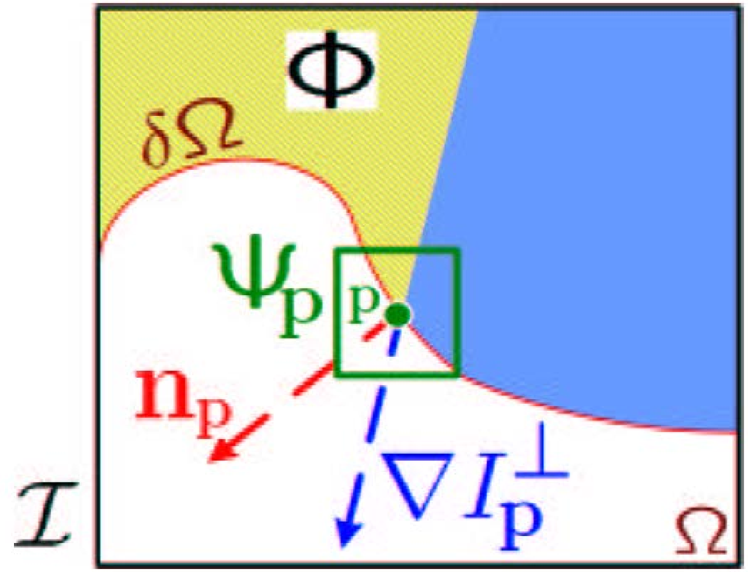
- "The data term tends to push isophotes rapidly inward, while the confidence term tends to suppress precisely this sort of incursion into the target region. As presented in the results section, this balance is handled gracefully via the mechanism of a single priority computation for all patches on the fill front."



Initialization

$$C(\mathbf{p}) \; = \; 0 \;\; \forall \mathbf{p} \in \Omega$$

$$C(\mathbf{p}) = 1 \;\; \forall \mathbf{p} \in \mathcal{I} - \Omega$$

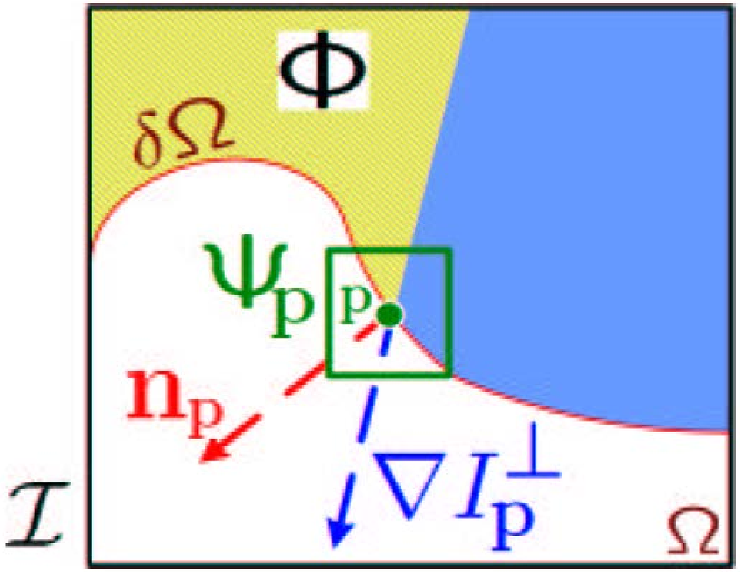


Computing Patch Priorities

- Best-first
  - Patches which are on the continuation of strong edges and which are surrounded by high-confidence pixels

$$P(\mathbf{p}) = C(\mathbf{p})D(\mathbf{p}) \qquad \mathbf{p} \in \delta\Omega$$

priority = confidence term * data term



Propagating Texture and Structure Information

- Search in the source region for the patch most similar to $\Psi_{\hat{\mathbf{p}}}$

$$\Psi_{\hat{\mathbf{q}}} = \arg\min_{\Psi_{\mathbf{q}} \in \Phi} d(\Psi_{\hat{\mathbf{p}}}, \Psi_{\mathbf{q}})$$

- Distance between two patches: sum of squared difference (SSD)
- CIE Lab color space

- Copy the value of each pixel-to-be-filled in $\Psi_{\hat{\mathbf{p}}} \cap \Omega$ from its corresponding position in $\Psi_{\hat{\mathbf{q}}}$
  - Patch-based, fast

Updating Confidence Values

$$C(\mathbf{q}) = C(\hat{\mathbf{p}}) \quad \forall \mathbf{q} \in \Psi_{\hat{\mathbf{p}}} \cap \Omega$$

- As filling proceeds, confidence values decay
  - Less sure of the values of pixels near the center of the target region

Region Filling Algorithm

Extract the manually selected initial front $\delta\Omega^0$.

Repeat until done:

1a. Identify the fill front $\delta\Omega^t$. If $\Omega^t = \emptyset$, exit.

1b. Compute priorities $P(\mathbf{p}) \quad \forall \mathbf{p} \in \delta\Omega^t$.

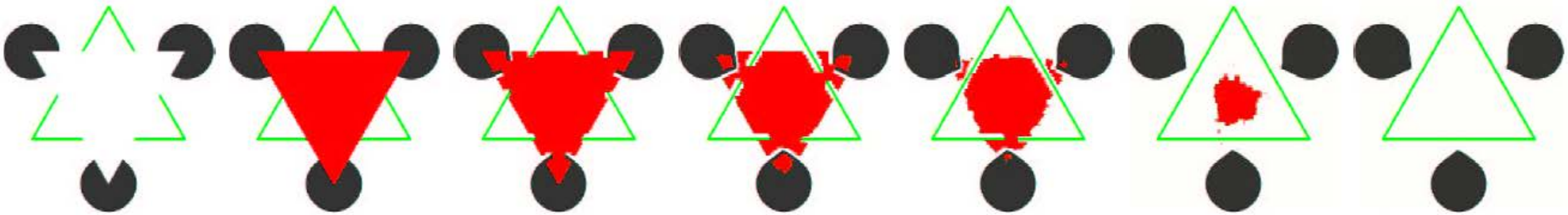
2a. Find the patch $\Psi_{\hat{\mathbf{p}}}$ with the maximum priority, *i.e.*, $\Psi_{\hat{\mathbf{p}}} \mid \hat{\mathbf{p}} = \arg\max_{\mathbf{p} \in \delta\Omega^t} P(\mathbf{p})$

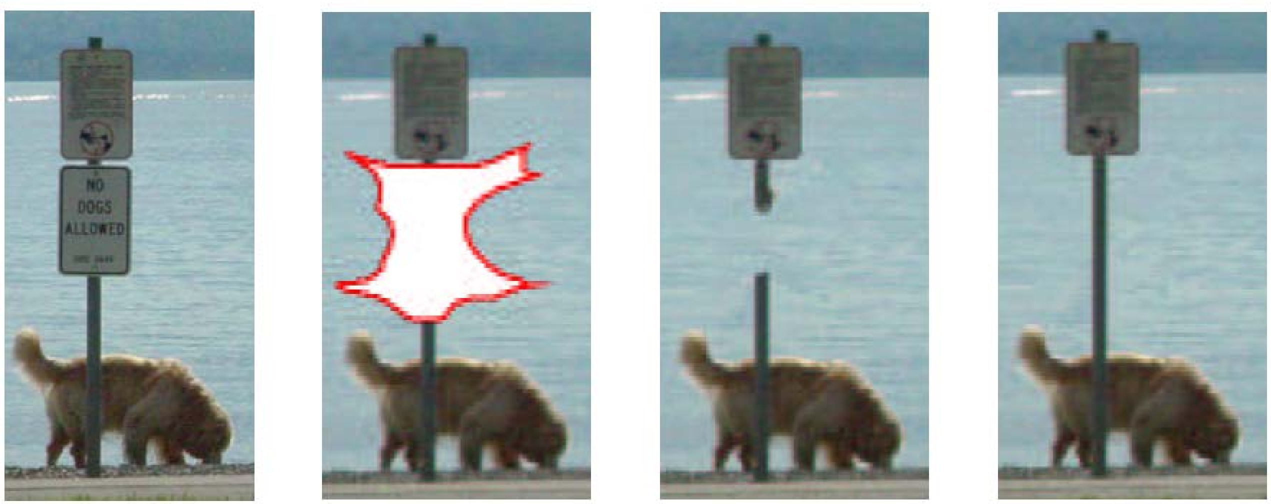
2b. Find the exemplar $\Psi_{\hat{\mathbf{q}}} \in \Phi$ that minimizes $d(\Psi_{\hat{\mathbf{p}}}, \Psi_{\hat{\mathbf{q}}})$.

2c. Copy image data from $\Psi_{\hat{\mathbf{q}}}$ to $\Psi_{\hat{\mathbf{p}}}$.

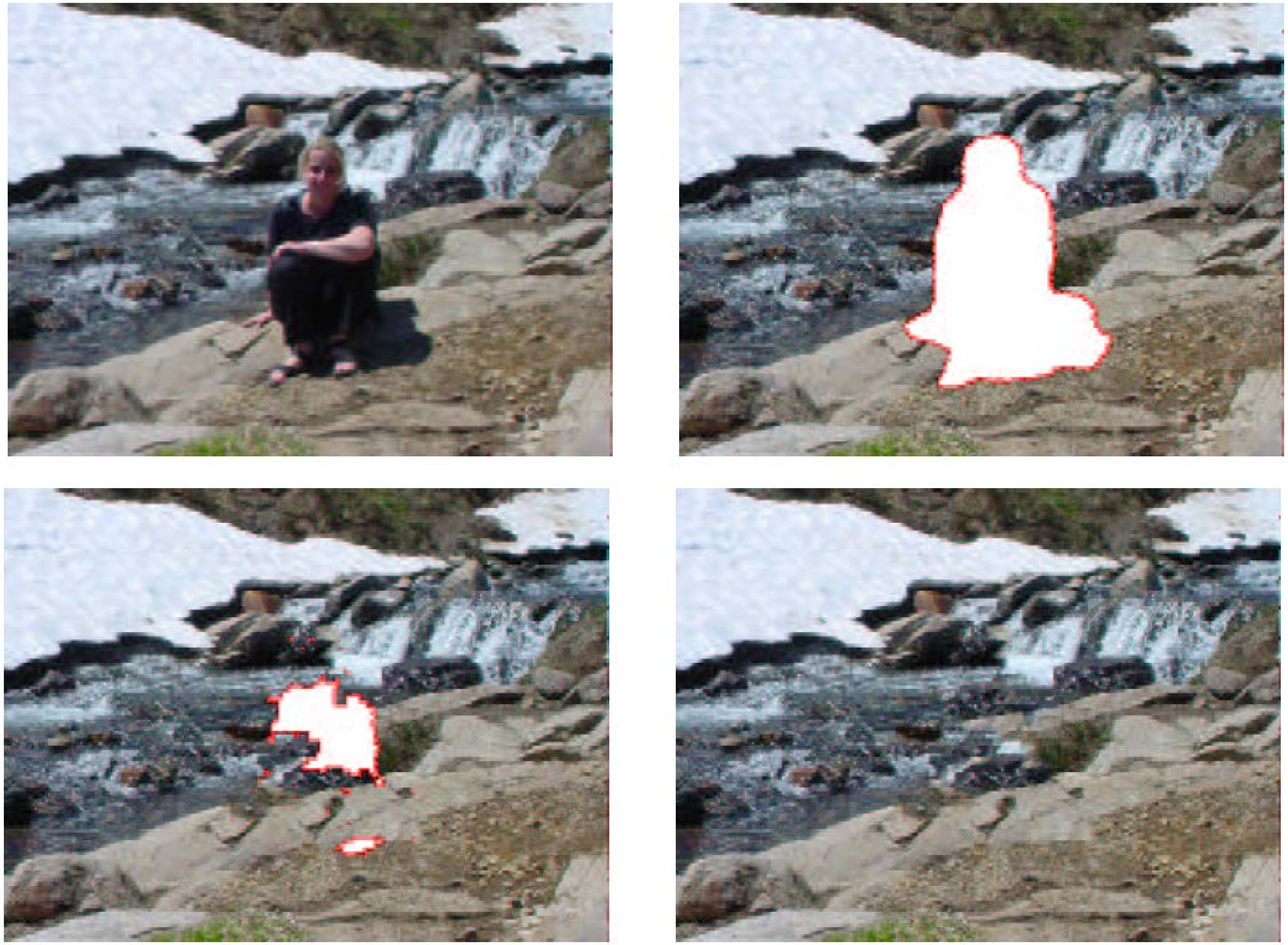
3. Update $C(\mathbf{p}) \;\; \forall \mathbf{p} \;\; |\mathbf{p} \in \Psi_{\hat{\mathbf{p}}} \cap \Omega$

Results





Results



Questions?

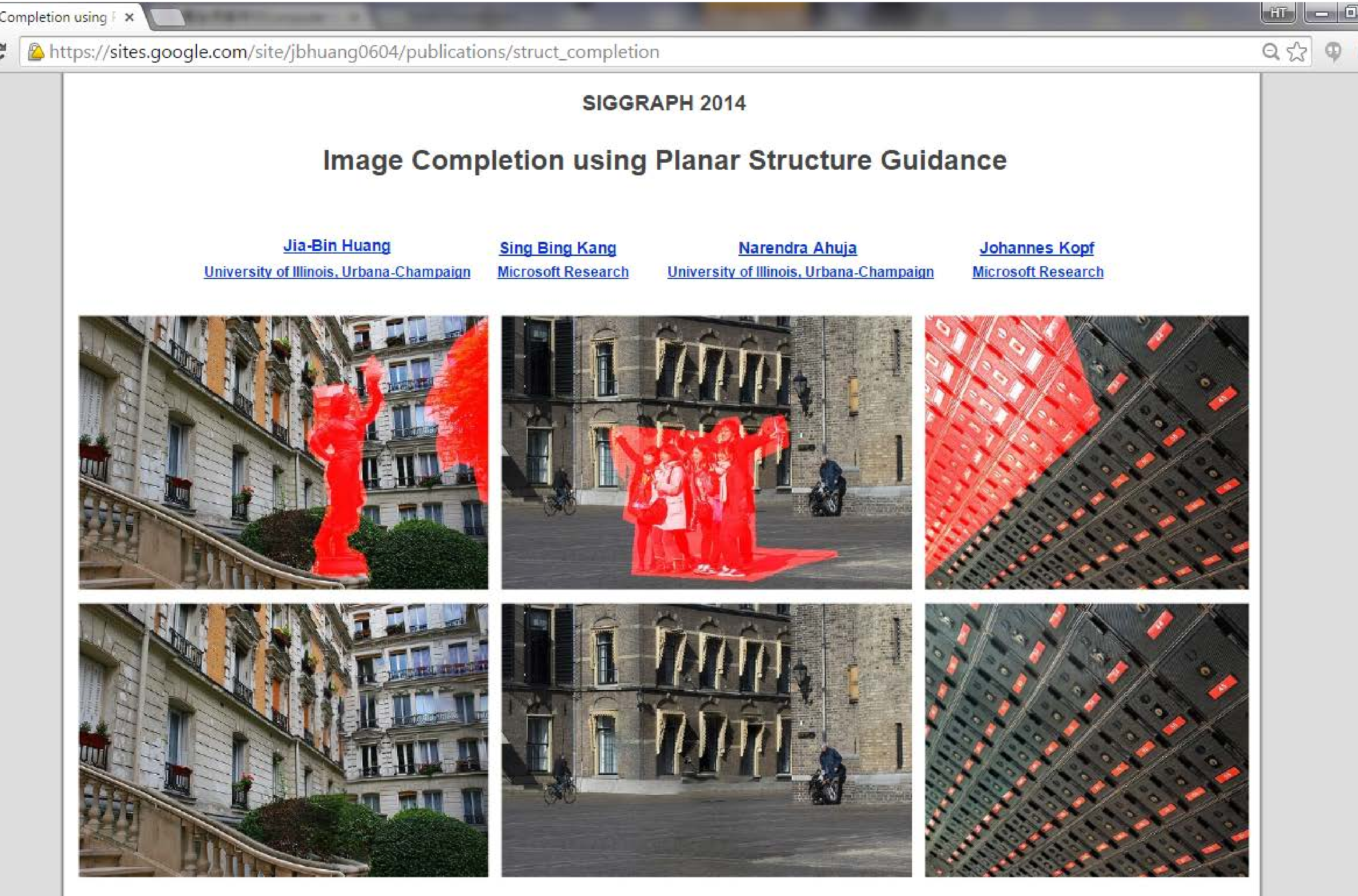
Summary

- A fast method to replicate both texture and structure

- Filling the region in a right ordering
  → linear structure preserved

- Priority = confidence term * data term

Further Reading



Sparse Representation for Color Image Restoration

- J. Mairal, M. Elad, and G. Sapiro.
  - IEEE Transactions on Image Processing. volume 17, issue 1, January 2008, pages 53-69.
  - **Online Dictionary Learning for Sparse Coding**
    - J. Mairal, F. Bach, J. Ponce, and G. Sapiro
    - ICML 2009

Principal Component Analysis (PCA)

$$\min_{\mathsf{D}} \sum_i ||\mathbf{x}_i - \mathsf{D}\mathsf{D}^\mathsf{T}\mathbf{x}_i||_2^2$$

$$\mathsf{D}^\mathsf{T}\mathbf{x}_i = \boldsymbol{\alpha}_i$$

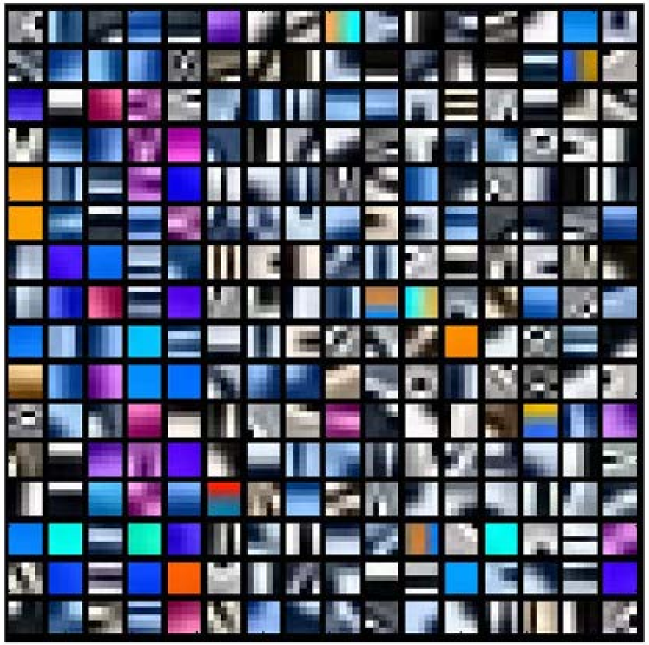
$$\mathsf{D}^\mathsf{T}\mathsf{D} = \mathsf{I}$$

Sparse Representation

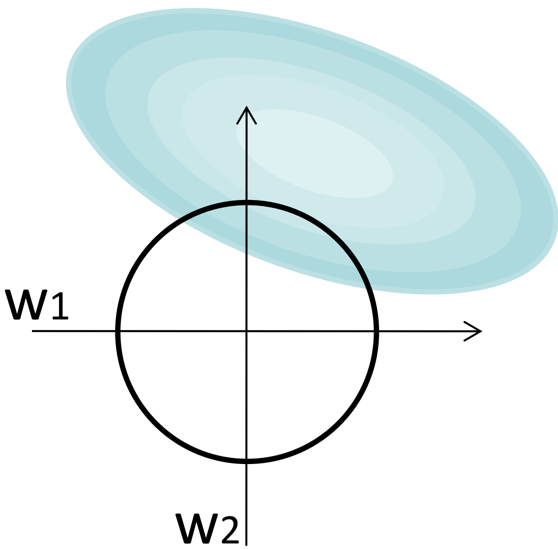
› Dictionary learning

$$\min_{\substack{\boldsymbol{\alpha}\in\mathbb{R}^{p\times n}\\ \mathbf{D}\in\mathcal{C}}} \sum_{i=1}^{n} \frac{1}{2}||\mathbf{x}_i - \mathbf{D}\boldsymbol{\alpha}_i||_2^2 + \lambda||\boldsymbol{\alpha}_i||_1$$

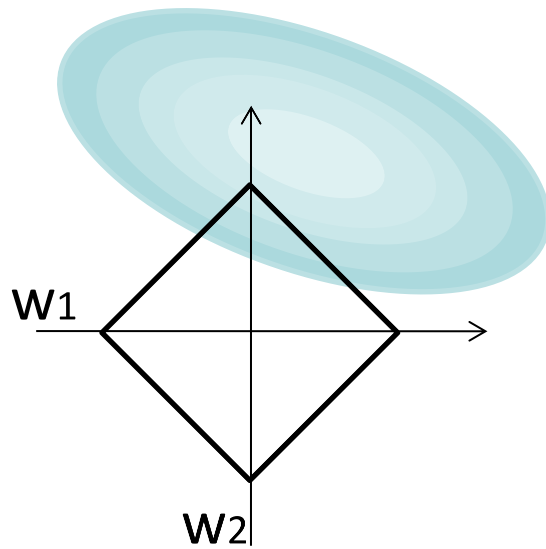
$$\mathcal{C} \triangleq \{\mathbf{D} \in \mathbb{R}^{m\times p} \;\; \text{s.t.} \;\; \forall j = 1,\ldots,p, \;\; ||\mathbf{d}_j||_2 \leq 1\}.$$



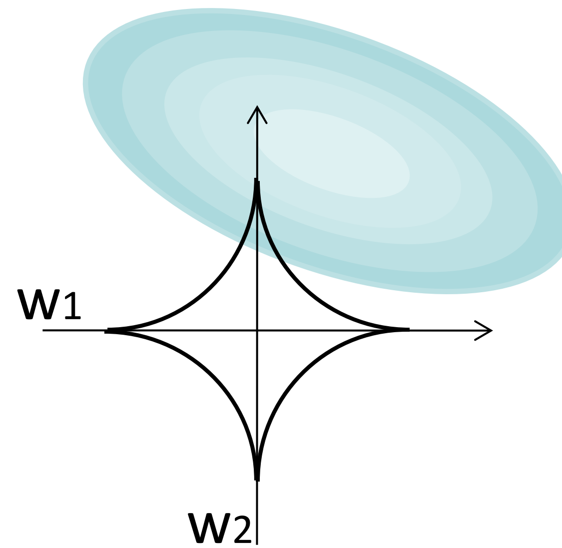
L1 Norm? Sparse?



L_2 norm



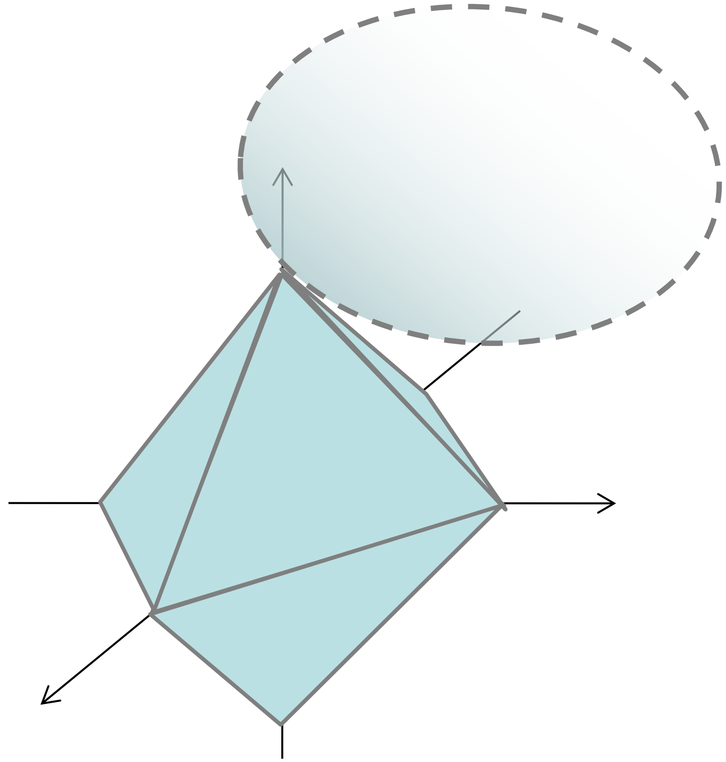
L_1 norm



L_p norm, $p<1$

zero norm?

Higher Dimension



Online Dictionary Learning

Require: $\mathbf{D}_0 \in \mathbb{R}^{m \times p}$ (initial dictionary); $\lambda \in \mathbb{R}$

1: $\mathbf{A}_0 = 0$, $\mathbf{B}_0 = 0$.

2: **for** t=1,...,T **do**

3: Draw $\mathbf{x}_t$

4: Sparse Coding

$$\boldsymbol{\alpha}_t \leftarrow \arg\min_{\boldsymbol{\alpha} \in \mathbb{R}^p} \frac{1}{2}||\mathbf{x}_t - \mathbf{D}_{t-1}\boldsymbol{\alpha}||_2^2 + \lambda||\boldsymbol{\alpha}||_1,$$

5: Aggregate sufficient statistics

$\mathbf{A}_t \leftarrow \mathbf{A}_{t-1} + \boldsymbol{\alpha}_t\boldsymbol{\alpha}_t^T$, $\mathbf{B}_t \leftarrow \mathbf{B}_{t-1} + \mathbf{x}_t\boldsymbol{\alpha}_t^T$

6: Dictionary Update (block-coordinate descent)

$$\mathbf{D}_t \leftarrow \arg\min_{\mathbf{D} \in \mathcal{C}} \frac{1}{t}\sum_{i=1}^{t}\Big(\frac{1}{2}||\mathbf{x}_i - \mathbf{D}\boldsymbol{\alpha}_i||_2^2 + \lambda||\boldsymbol{\alpha}_i||_1\Big).$$

7: **end for**

$$\arg\min_{\mathbf{D} \in \mathcal{C}} \frac{1}{t}\Big(\frac{1}{2}\operatorname{Tr}(\mathbf{D}^T\mathbf{D}\mathbf{A}_t) - \operatorname{Tr}(\mathbf{D}^T\mathbf{B}_t)\Big)$$

[Mairal, Elad, and Sapiro., 2008]

$$\min_{\mathbf{D}\in\mathcal{C},\boldsymbol{\alpha}} \sum_i \frac{1}{2}||\boldsymbol{\beta}_i \otimes (\mathbf{y}_i - \mathbf{D}\boldsymbol{\alpha}_i)||_2^2 + \lambda_i \psi(\boldsymbol{\alpha}_i)$$

[Mairal, Elad, and Sapiro., 2008]

Inpainting a 12M-pixel Image [Mairal *et al.*]

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Conclusion

- Sparse coding, sparse representation
  - ICCV tutorial on sparse coding and dictionary learning for image processing http://lear.inrialpes.fr/people/mairal/tutorial_iccv09/
  - Compressive sensing http://dsp.rice.edu/cs

Goal of This Course

- Literature survey
  - How to solve interesting image problems
  - Learn mathematical modeling techniques
  - Come up with new ideas and find new applications
- Hands-on experience
  - 10+ Assignments
- Doing research
  - Term project

read think try create →

Related Topics

- Optimization
  - Maximizing joint/conditional probabilities
  - Minimizing cost/error functions
- Image representations
  - Markov random fields
  - Vector fields
- Math
  - Linear algebra, numerical methods, probability