Medical image formation using machine learning

Jeffrey A. Fessler
William L. Root Professor of EECS

EECS Dept., BME Dept., Dept. of Radiology
University of Michigan

http://web.eecs.umich.edu/~fessler

Work with Sai Ravishankar, Il Yong Chun, Raj Nadakuditi,
Yong Long, Xuehang Zheng, ...

ECE informal faculty seminar

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Summary

[redacted] medical [redacted] machine [redacted] learning [redacted]

Background

- Forward problem (data acquisition):

  Scene Objects $\xrightarrow[\boldsymbol{x}]{\text{physics}}$ Imaging System $\rightarrow$ raw data $\boldsymbol{y}$

  SPECT, PET, X-ray CT, MRI, optical

- Inverse problem (image formation):

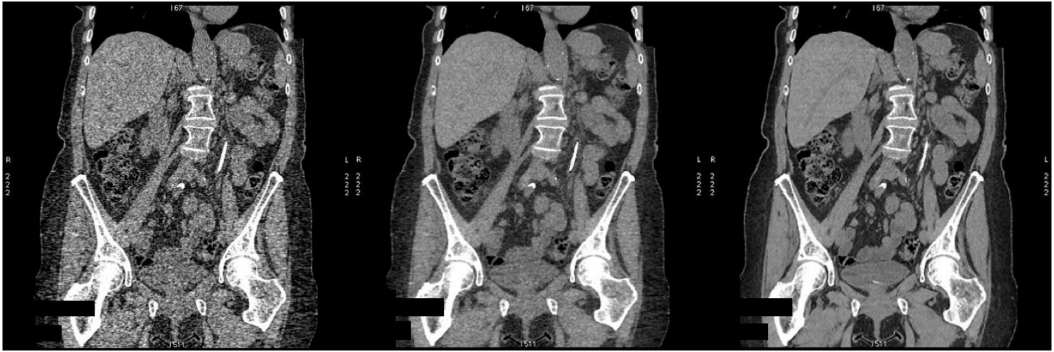
  Acquire Data $\xrightarrow[\boldsymbol{y}]{\text{raw data}}$ Reconstruct Images $\rightarrow$ images $\hat{\boldsymbol{x}}$

- Image reconstruction topics: physics models, measurement statistical models, regularization / object priors, optimization.

Generations of medical image reconstruction methods

1. 70's "Analytical" methods (integral equations)
   FBP for SPECT / PET / X-ray CT, IFFT for MRI, ...
2. 80's Algebraic methods (as in "linear algebra")
   Solve $\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x}$
3. 90's Statistical methods
   - LS / ML methods
   - regularized / Bayesian methods
4. 00's Compressed sensing methods
   (mathematical sparsity models)
5. 10's Adaptive / data-driven methods
   machine learning, deep learning, ...

- A picture is worth 1000 words
- (and perhaps several 1000 seconds of computation?)



Thin-slice FBP	ASIR (denoise)	Statistical
Seconds	A bit longer	Much longer

Today's talk: less about computation, more about image quality
Right image used edge-preserving regularization

Safety / health relevance: X-ray dose and diagnostic accuracy

History: Milestones in iterative image reconstruction

Commercial availability of iterative methods for human scanners per FDA 510(k) dates:

- PET/SPECT
  Unregularized OS-EM $\approx$ 1997
- X-ray CT
  Regularized MBIR [2011-11-09 for GE Veo]
  (Installed at UM in Jan. 2012)
- PET
  Regularized EM variant (Q.Clear) 2014-03-21
- MRI
  Compressed sensing! (Sparsity-based regularization)
  [2017-01-27 for Siemens Cardiac Cine]
  [2017-04-20 for GE HyperSense]
- Ultrasound?

(a) 4× under-sampled MR k-space

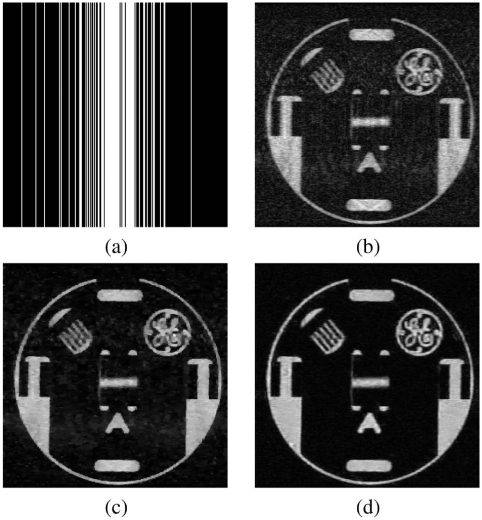
(b) zero-filled reconstruction

(c) "compressed sensing" reconstruction with TV regularization

(d) adaptive dictionary learning regularization [1, Fig. 10]

Safety / health relevance:

- scan time
- motion
- image quality



Outline

Ill-posed inverse problems

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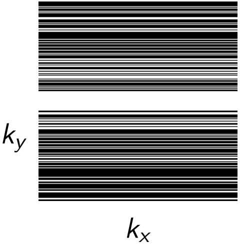
$$\boldsymbol{y} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{\varepsilon}$$

$\boldsymbol{y}$: measurements $\qquad \boldsymbol{\varepsilon}$: noise

$\boldsymbol{x}$: unknown image $\qquad \boldsymbol{A}$: system matrix (typically wide)

- compressed sensing (*e.g.*, MRI) ($\boldsymbol{A}$ "random" rows of DFT)



- deblurring (restoration) ($\boldsymbol{A}$ Toeplitz)
- in-painting ($\boldsymbol{A}$ subset of rows of $\boldsymbol{I}$)
- denoising (not ill posed) ($\boldsymbol{A} = \boldsymbol{I}$)

Why under-sample?

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Why under-sample in MRI?

- Reduce scan time (?)
  - Patient comfort
  - Scan cost / throughput
  - Motion artifacts (Philips at ISMRM 2017)
- Improve spatial resolution (collect higher k-space lines)
- Improve scan diversity for quantitative MRI
- Improve temporal resolution trade-off in dynamic MRI

Why under-sample or reduce intensity in CT?

- Reduce X-ray dose

(But under-sampling leads to ill-posed inverse problems...)

Inverse problems via MAP estimation

Unknown image $\boldsymbol{x}$ $\rightarrow$ $\boxed{\text{System model } \mathrm{p}(\boldsymbol{y} \,|\, \boldsymbol{x})}$ $\rightarrow$ Data $\boldsymbol{y}$ $\rightarrow$ $\boxed{\text{Estimator}}$ $\rightarrow$ Recon. image $\hat{\boldsymbol{x}}$

If we have a prior $\mathrm{p}(\boldsymbol{x})$, then the MAP estimate is:

$$\hat{\boldsymbol{x}} = \arg\max_{\boldsymbol{x}} \mathrm{p}(\boldsymbol{x} \,|\, \boldsymbol{y}) = \arg\max_{\boldsymbol{x}} \log \mathrm{p}(\boldsymbol{y} \,|\, \boldsymbol{x}) + \log \mathrm{p}(\boldsymbol{x}) \, .$$

For gaussian measurement errors and a linear forward model:

$$-\log \mathrm{p}(\boldsymbol{y} \,|\, \boldsymbol{x}) \equiv \frac{1}{2} \|\boldsymbol{y} - \boldsymbol{A}\boldsymbol{x}\|_{\boldsymbol{W}}^2$$

where $\|\boldsymbol{y}\|_{\boldsymbol{W}}^2 = \boldsymbol{y}' \boldsymbol{W} \boldsymbol{y}$ and $\boldsymbol{W}^{-1} = \mathrm{Cov}\{\boldsymbol{y} \,|\, \boldsymbol{x}\}$ is known

($\boldsymbol{A}$ from physics, $\boldsymbol{W}$ from statistics)

Priors for MAP estimation

- If all images $\boldsymbol{x}$ are "plausible" (have non-zero probability) then

$$\mathrm{p}(\boldsymbol{x}) \propto \mathrm{e}^{-\mathsf{R}(\boldsymbol{x})} \Longrightarrow -\log \mathrm{p}(\boldsymbol{x}) \equiv \mathsf{R}(\boldsymbol{x})$$

  (from fantasy / imagination / wishful thinking / data)

- MAP $\equiv$ regularized weighted least-squares (WLS) estimation:

$$\begin{aligned}\hat{\boldsymbol{x}} &= \arg\max_{\boldsymbol{x}} \; \log \mathrm{p}(\boldsymbol{y} \mid \boldsymbol{x}) + \log \mathrm{p}(\boldsymbol{x}) \\ &= \arg\min_{\boldsymbol{x}} \; \frac{1}{2} \|\boldsymbol{y} - \boldsymbol{A}\boldsymbol{x}\|_{\boldsymbol{W}}^2 + \mathsf{R}(\boldsymbol{x})\end{aligned}$$

- A regularizer $\mathsf{R}(\boldsymbol{x})$, aka log prior, is essential for high-quality solutions to ill-conditioned / ill-posed inverse problems.
- Why ill-posed? Often high ambitions...

Classical regularizers ("hand crafted")

- Tikhonov regularization (IID gaussian prior)
- Roughness penalty (Basic MRF prior)
- Sparsity in ambient space
- Edge-preserving regularization
- Total-variation (TV) regularization
- Black-box denoiser like NLM

Edge-preserving regularization

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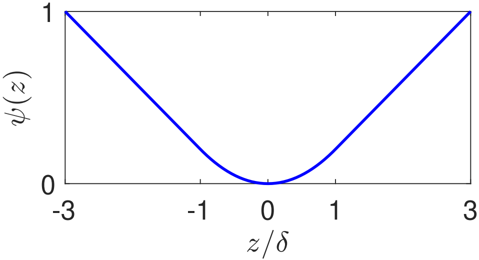
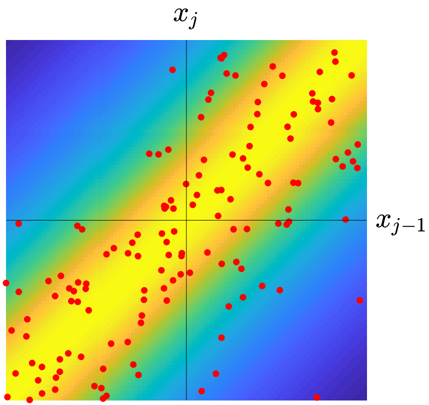
Neighboring pixels tend to have similar values except near edges:

$$\mathsf{R}(\boldsymbol{x}) = \beta \sum_j \psi(x_j - x_{j-1})$$

Potential function ψ:





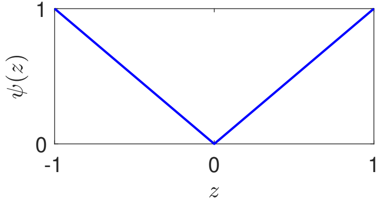
- Equivalent to improper prior (agnostic to DC value)
- Accounts for spatial correlations, but only very locally
- Used clinically now for low-dose X-ray CT image reconstruction

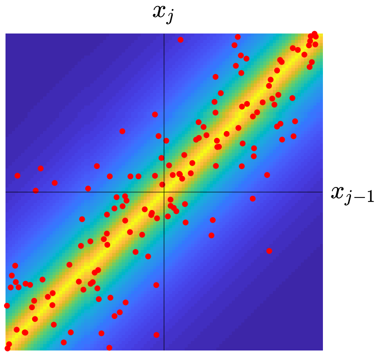
Total-variation (TV) regularization

Neighboring pixels tend to have similar values except near edges ("gradient sparsity"):

$$\mathsf{R}(\boldsymbol{x}) = \beta \,\mathrm{TV}(\boldsymbol{x}) = \beta \left\| \boldsymbol{\Delta x} \right\|_1$$
$$= \beta \sum_j |x_j - x_{j-1}|$$

Potential function ψ:





- Equivalent to improper prior (agnostic to DC value)
- Accounts for correlations, but only very locally
- Well-suited to piece-wise constant Shepp-Logan phantom!
- Used in many academic publications...

Many more "conventional" regularizers / priors

- Transforms: wavelets, curvelets, ...
- Markov random field models
- Graphical models
- ...

All "hand crafted" ...

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- Data
  - Population adaptive methods (*e.g.*, X-ray CT)
  - Patient adaptive methods (*e.g.*, dynamic MRI?)
- Spatial structure
  - Patch-based models
  - Convolutional models
- Regularizer formulation
  - Synthesis (dictionary) approach
  - Analysis (sparsifying transforms) approach

Many options...

Outline

- Data
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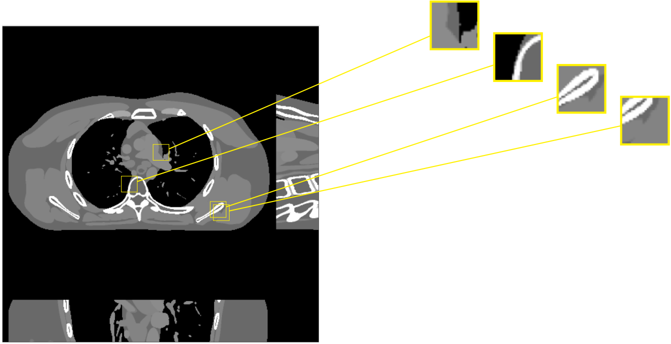
  - Convolutional models
- Regularizer formulation
  - Synthesis (dictionary) approach
  - Analysis (sparsifying transform) approach

Patch-wise transform sparsity model

Assumption: if $\boldsymbol{x}$ is a plausible image, then each $\boldsymbol{\Omega} \boldsymbol{P}_m \boldsymbol{x}$ is sparse.

- $\boldsymbol{P}_m \boldsymbol{x}$ extracts the mth of M patches from $\boldsymbol{x}$
- $\boldsymbol{\Omega}$ is a square sparsifying transform matrix



Sparsifying transform learning (population adaptive)

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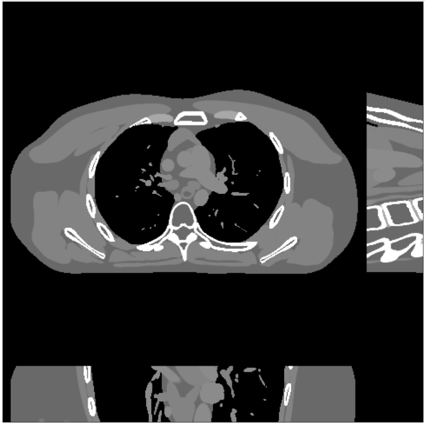
Given training images $\boldsymbol{x}_1, \ldots, \boldsymbol{x}_L$ from a representative population, find transform $\boldsymbol{\Omega}_*$ that best sparsifies their patches:

$$\boldsymbol{\Omega}_* = \operatorname*{arg\,min}_{\boldsymbol{\Omega} \text{ unitary}} \min_{\{\boldsymbol{z}_{l,m}\}} \sum_{l=1}^{L} \sum_{m=1}^{M} \|\boldsymbol{\Omega} \boldsymbol{P}_m \boldsymbol{x}_l - \boldsymbol{z}_{l,m}\|_2^2 + \alpha \|\boldsymbol{z}_{l,m}\|_0$$

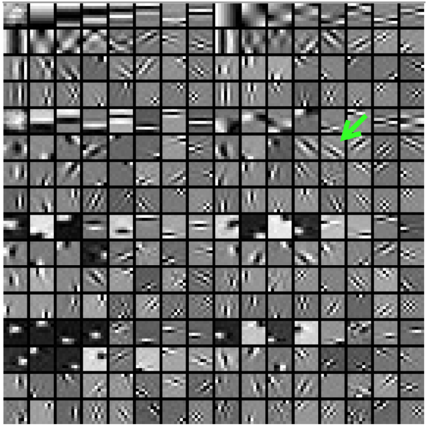
- Encourage aggregate sparsity, not patch-wise sparsity (cf K-SVD [2])
- Non-convex due to unitary constraint and $\|\cdot\|_0$
- Efficient alternating minimization algorithm [3]
  - $\boldsymbol{z}$ update : simple hard thresholding
  - $\boldsymbol{\Omega}$ update : orthogonal Procrustes problem (SVD)
  - Subsequence convergence guarantees [3]

Example of learned sparsifying transform

3D X-ray training data



Parts of learned sparsifier $\mathbf{\Omega}_*$



(2D slices in x-y, x-z, y-z, from 3D image volume)

$8 \times 8 \times 8$ patches $\Longrightarrow$ $\mathbf{\Omega}_*$ is $8^3 \times 8^3 = 512 \times 512$

top 8×8 slice of 256 of the 512 rows of $\mathbf{\Omega}_*$ $\uparrow$

Regularizer based on learned sparsifying transform

Regularized inverse problem [4]:

$$\hat{\boldsymbol{x}} = \arg\min_{\boldsymbol{x}} \|\boldsymbol{A}\boldsymbol{x} - \boldsymbol{y}\|_{\boldsymbol{W}}^2 + \beta\, \mathsf{R}(\boldsymbol{x})$$

$$\mathsf{R}(\boldsymbol{x}) = \min_{\{\boldsymbol{z}_m\}} \sum_{m=1}^{M} \|\boldsymbol{\Omega}_* \boldsymbol{P}_m \boldsymbol{x} - \boldsymbol{z}_m\|_2^2 + \alpha \|\boldsymbol{z}_m\|_0 .$$

$\boldsymbol{\Omega}_*$ adapted to population training data

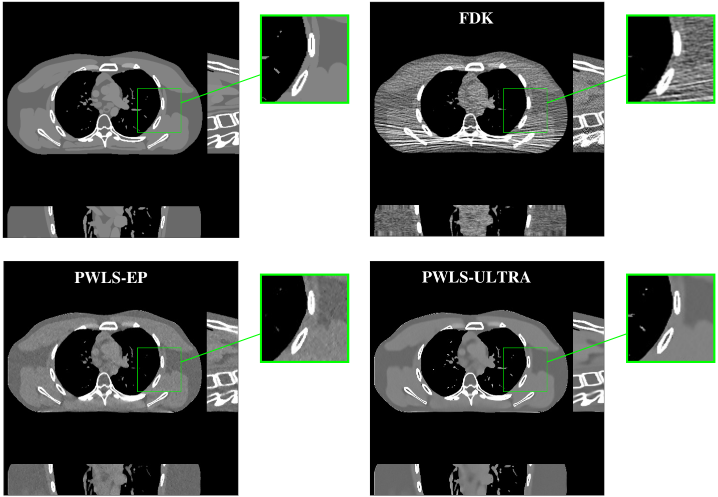
Alternating minimization optimizer:

- $\boldsymbol{z}_m$ update : simple hard thresholding
- $\boldsymbol{x}$ update : quadratic problem (many options)

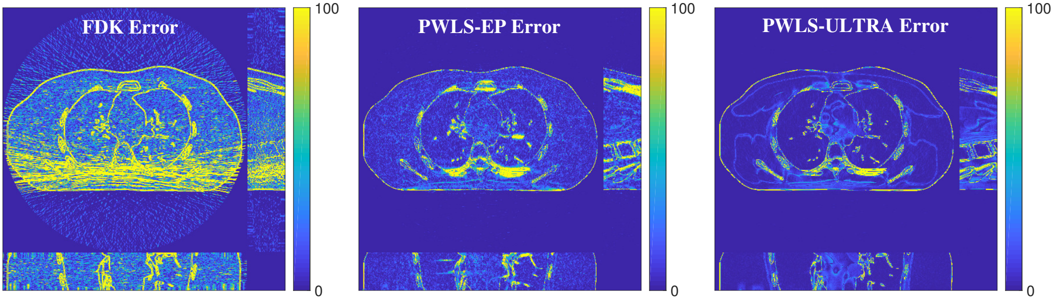
  Linearized augmented Lagrangian method (LALM) [5]

Example: low-dose 3D X-ray CT simulation

X. Zheng, S. Ravishankar, Y. Long, JF: IEEE T-MI, June 2018 [4]



3D X-ray CT simulation Error maps



	X-ray Intensity	FDK	EP	ST Ω_*	ULTRA	ULTRA-$\{\tau_j\}$
RMSE in HU	1×10^4	67.8	34.6	32.1	30.7	**29.2**
	5×10^3	89.0	41.1	37.3	35.7	**34.2**

- Physics / statistics provides dramatic improvement
- Data adaptive regularization further reduces RMSE

Given training images $\boldsymbol{x}_1, \ldots, \boldsymbol{x}_L$ from a representative population, find a set of transforms $\left\{\hat{\boldsymbol{\Omega}}_k\right\}_{k=1}^K$ that best sparsify image patches:

$$\left\{\hat{\boldsymbol{\Omega}}_k\right\} = \mathop{\arg\min}_{\{\boldsymbol{\Omega}_k \text{ unitary}\}} \min_{\left\{k_{l,m} \in \{1,\ldots,K\}\right\}} \min_{\left\{\boldsymbol{z}_{l,m}\right\}} \sum_{l=1}^{L} \sum_{m=1}^{M} \left\| \boldsymbol{\Omega}_{k_{l,m}} \boldsymbol{P}_m \boldsymbol{x}_l - \boldsymbol{z}_{l,m} \right\|_2^2 + \alpha \left\| \boldsymbol{z}_{l,m} \right\|_0$$

- Joint unsupervised clustering / sparsification
- Further nonconvexity due to clustering
- Efficient alternating minimization algorithm [6]

Example: 3D X-ray CT learned set of transforms

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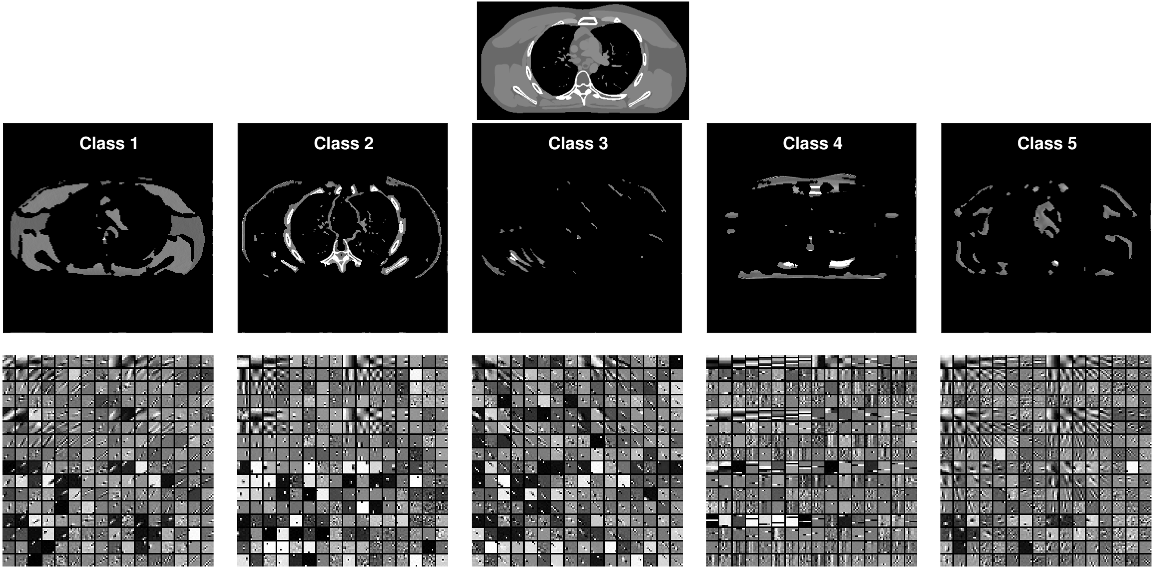
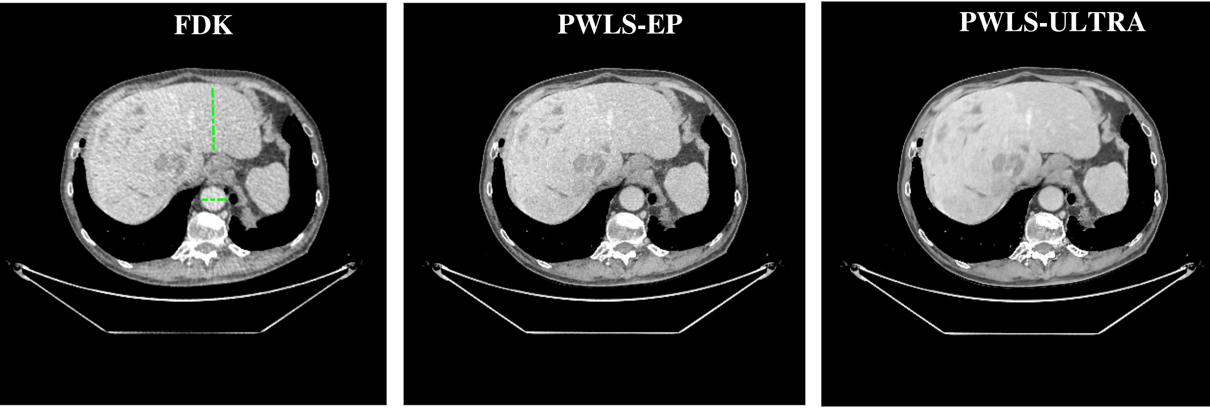


Example: 3D X-ray CT ULTRA for chest scan



Zheng et al., IEEE T-MI, June 2018 [4]

Matlab code: `http://web.eecs.umich.edu/~fessler/irt/reproduce/`

`https://github.com/xuehangzheng/PWLS-ULTRA-for-Low-Dose-3D-CT-Image-Reconstruction`

Outline

- Data
  - Population adaptive methods
  - Patient adaptive methods
- Spatial structure
  - Patch-based models
  - Convolutional models
- Regularizer formulation
  - Synthesis (dictionary) approach
  - Analysis (sparsifying transform) approach

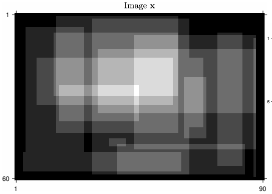
Drawback of basic patch-based methods:
$512 \times 512 \times 512$ 3D X-ray CT image volume
$8 \times 8 \times 8$ patches
$\Longrightarrow 512^3 \cdot 8^3 \cdot 4 = 256$ Gbyte of patch data for stride=1

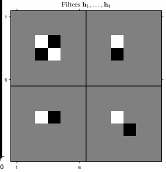
Convolutional sparsity: analysis model

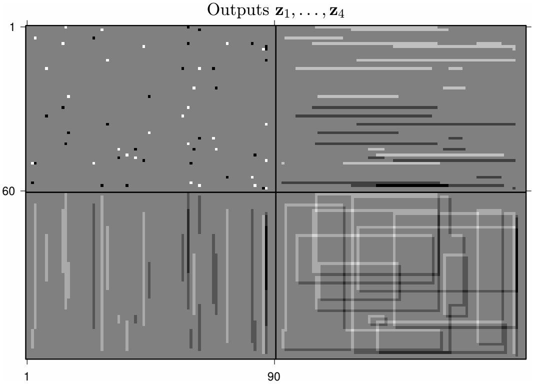
Assumption: For a plausible image $\boldsymbol{x}$, the filter outputs $\{\boldsymbol{h}_k * \boldsymbol{x}\}$ are sparse, for some filters $\{\boldsymbol{h}_k\}_{k=1}^{K}$ [7]

- For more plausible images, the outputs $\{\boldsymbol{h}_k * \boldsymbol{x}\}$ are more sparse.
- $*$ denotes convolution
- Inherently shift invariant and no patches

Example (hand crafted filters):







Sparsifying filter learning (population adaptive)

Given training images $\boldsymbol{x}_1, \ldots, \boldsymbol{x}_L$ from a representative population, find filters $\left\{ \hat{\boldsymbol{h}}_k \right\}_{k=1}^{K}$ that best sparsify them:

$$\left\{ \hat{\boldsymbol{h}}_k \right\} = \mathop{\arg\min}_{\{\boldsymbol{h}_k\} \in \mathcal{H}} \min_{\{\boldsymbol{z}_{l,k}\}} \sum_{l=1}^{L} \sum_{k=1}^{K} \left\| \boldsymbol{h}_k * \boldsymbol{x}_l - \boldsymbol{z}_{l,k} \right\|_2^2 + \alpha \left\| \boldsymbol{z}_{l,k} \right\|_0$$

- To encourage filter diversity:
  - $\mathcal{H} = \{\boldsymbol{H} : \boldsymbol{H}\boldsymbol{H}' = \boldsymbol{I}\}, \ \boldsymbol{H} = [\boldsymbol{h}_1 \ \ldots \ \boldsymbol{h}_K]$
  - *cf.* tight-frame condition $\sum_{k=1}^{K} \|\boldsymbol{h}_k * \boldsymbol{x}\|_2^2 \propto \|\boldsymbol{x}\|_2^2$
- Encourage aggregate sparsity, period
- Non-convex due to constraint $\mathcal{H}$ and $\|\cdot\|_0$
- Efficient alternating minimization algorithm [8]
  - $\boldsymbol{z}$ update is simply hard thresholding
  - Filter update uses diagonal majorizer, proximal map (SVD)
  - Subsequence convergence guarantees [8]

Examples of learned sparsifying filters

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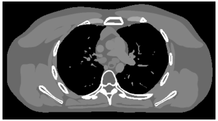
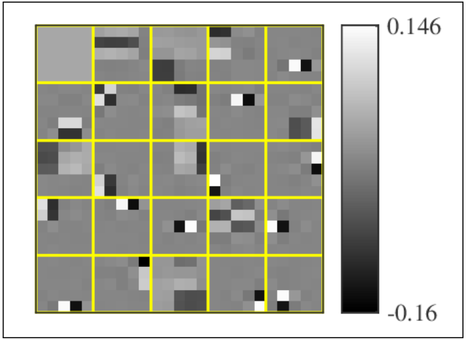
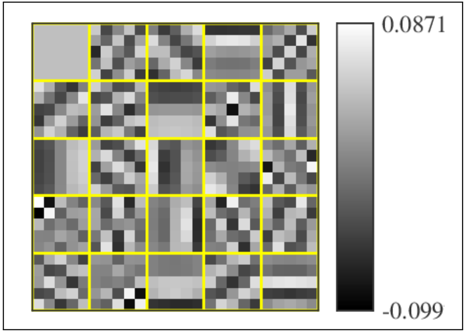
2D X-ray CT training data and learned 5×5 sparsifying filters $\left\{ \hat{\boldsymbol{h}}_k \right\}$ [8]:





$\alpha = 10^{-4}$



$\alpha = 2 \times 10^{-3}$

Regularizer based on learned sparsifying filters

Regularized inverse problem [8]:

$$\hat{\boldsymbol{x}} = \operatorname*{arg\,min}_{\boldsymbol{x} \succeq \boldsymbol{0}} \|\boldsymbol{A}\boldsymbol{x} - \boldsymbol{y}\|_{\boldsymbol{W}}^2 + \beta\, \mathsf{R}(\boldsymbol{x})$$

$$\mathsf{R}(\boldsymbol{x}) = \operatorname*{arg\,min}_{\{\boldsymbol{z}_k\}} \sum_{k=1}^{K} \left\| \hat{\boldsymbol{h}}_k * \boldsymbol{x} - \boldsymbol{z}_k \right\|_2^2 + \alpha \|\boldsymbol{z}_k\|_0 .$$

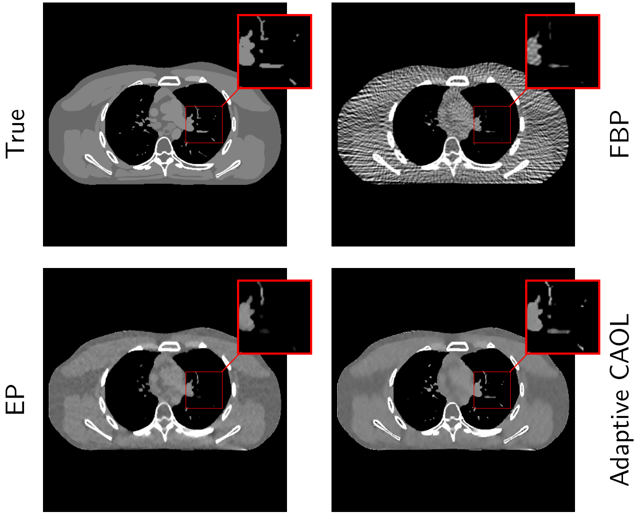
$\left\{ \hat{\boldsymbol{h}}_k \right\}$ adapted to population training data

Block proximal gradient with majorizer (BPG-M) optimizer:

- $\boldsymbol{z}_k$ update is simple hard thresholding
- $\boldsymbol{x}$ update is a quadratic problem: diagonal majorizer

I. Y. Chun, JF, 2018, arXiv 1802.05584 [8]

Example: sparse-view 2D X-ray CT simulation



Quantitative results

123 views (out of usual 984) $\Longrightarrow$ $8\times$ dose reduction

RMSE (in HU):

FBP	82.8
EP	40.8
Adaptive filters	**35.2**

- Physics / statistics provides dramatic improvement
- Data-adaptive regularization further reduces RMSE

Extension to multiple layers (cf CNN) I

Convolutional sparsity model: $\boldsymbol{h}_k * \boldsymbol{x}$ is sparse for $k = 1, \ldots, K_1$

Learning 1 "layer" of filters:

$$\{\hat{\boldsymbol{h}}_k^{[1]}\} = \mathop{\arg\min}_{\{\boldsymbol{h}_k^{[1]}\} \in \mathcal{H}} \min_{\{\boldsymbol{z}_{l,k}^{[1]}\}} \sum_{l=1}^{L} \sum_{k=1}^{K_1} \left\| \boldsymbol{h}_k^{[1]} * \boldsymbol{x}_l - \boldsymbol{z}_{l,k}^{[1]} \right\|_2^2 + \alpha \left\| \boldsymbol{z}_{l,k}^{[1]} \right\|_0$$

Extension to multiple layers (cf CNN) II

Learning 2 layers of filters [8]:

$$\left(\{\hat{\boldsymbol{h}}_k^{[1]}\}, \{\hat{\boldsymbol{h}}_k^{[2]}\}\right) = \mathop{\arg\min}_{\{\boldsymbol{h}_k^{[1]}\},\{\boldsymbol{h}_k^{[2]}\}\in\mathcal{H}} \min_{\{\boldsymbol{z}_{l,k}^{[1]}\}} \min_{\{\boldsymbol{z}_{l,k}^{[2]}\}}$$
$$\sum_{l=1}^{L}\sum_{k=1}^{K_1} \left\|\boldsymbol{h}_k^{[1]} * \boldsymbol{x}_l - \boldsymbol{z}_{l,k}^{[1]}\right\|_2^2 + \alpha \left\|\boldsymbol{z}_{l,k}^{[1]}\right\|_0$$
$$+\sum_{l=1}^{L}\sum_{k=1}^{K_2} \left\|\boldsymbol{h}_k^{[2]} * \left(\boldsymbol{P}_k \boldsymbol{z}_l^{[1]}\right) - \boldsymbol{z}_{l,k}^{[2]}\right\|_2^2 + \alpha \left\|\boldsymbol{z}_{l,k}^{[2]}\right\|_0$$

Here $\boldsymbol{P}_k$ is a pooling operator for the output of first layer

Block proximal gradient with majorizer (BPG-M) optimizer

I. Y. Chun, JF, 2018, arXiv 1802.05584 [8]

Use multi-level learned filters as (interpretable?) regularizer for CT.

Outline

MR with adapted patch dictionary

- Data
  - Population adaptive methods
  - Patient adaptive methods
- Spatial structure
  - Patch-based models
  - Convolutional models
- Regularizer formulation
  - Synthesis (dictionary) approach
  - Analysis (sparsifying transform) approach

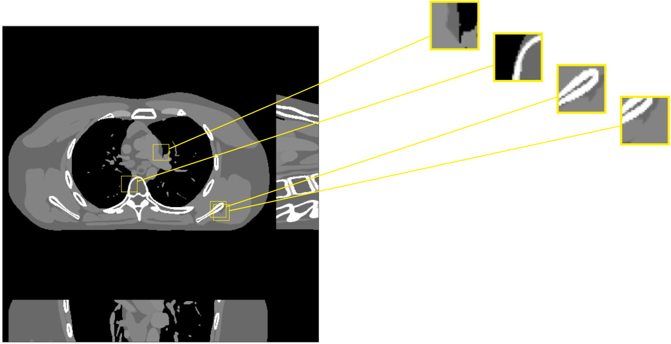
Patch-wise dictionary sparsity model

Assumption: if $\boldsymbol{x}$ is a plausible image, then each patch has

$$\boldsymbol{P}_p \boldsymbol{x} \approx \boldsymbol{D} \boldsymbol{z}_p,$$

for a sparse coefficient vector $\boldsymbol{z}_p$. (Synthesis approach.)

- $\boldsymbol{P}_p \boldsymbol{x}$ extracts the pth of P patches from $\boldsymbol{x}$
- $\boldsymbol{D}$ is a (typically overcomplete) dictionary for patches



MR reconstruction using adaptive dictionary regularizer

Dictionary-blind MR image reconstruction:

$$\hat{\boldsymbol{x}} = \arg\min_{\boldsymbol{x}} \frac{1}{2} \|\boldsymbol{A}\boldsymbol{x} - \boldsymbol{y}\|_2^2 + \beta\, \mathsf{R}(\boldsymbol{x})$$

$$\mathsf{R}(\boldsymbol{x}) = \min_{\boldsymbol{D} \in \mathcal{D}} \min_{\boldsymbol{Z}} \sum_{m=1}^{M} \left(\|\boldsymbol{P}_m \boldsymbol{x} - \boldsymbol{D}\boldsymbol{z}_m\|_2^2 + \lambda^2 \|\boldsymbol{z}_m\|_0 \right)$$

where $\boldsymbol{P}_m$ extracts mth of M image patches.

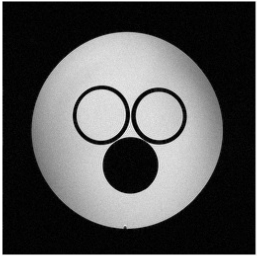
In words: of the many images...

Alternating (nested) minimization:

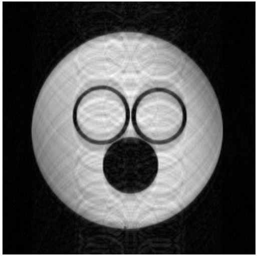
- Fixing $\boldsymbol{x}$ and $\boldsymbol{D}$, update each row of $\boldsymbol{Z} = [\boldsymbol{z}_1 \ \ldots \ \boldsymbol{z}_M]$ sequentially via hard-thresholding.
- Fixing $\boldsymbol{x}$ and $\boldsymbol{Z}$, update $\boldsymbol{D}$ using SOUP-DIL [9].
- Fixing $\boldsymbol{Z}$ and $\boldsymbol{D}$, updating $\boldsymbol{x}$ is a quadratic problem.
  - Efficient FFT solution for single-coil Cartesian MRI.
  - Use CG for non-Cartesian and/or parallel MRI.
- Non-convex, but monotone decreasing and some convergence theory [9].

2D CS MRI results I

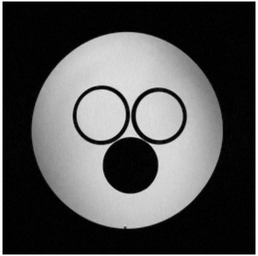
Fully Sampled



Zero-Filled



SOUP-DILLO-MRI



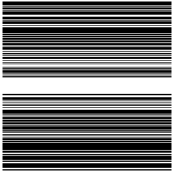
6×6 patches

$\boldsymbol{D} \in \mathbb{C}^{6^2 \times 144}$

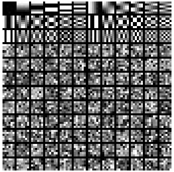
$\boldsymbol{D}_0$: [DCT | random]

[9]

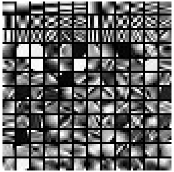
Sampling ($2.5\times$)



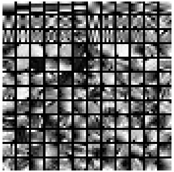
Initial $\boldsymbol{D}$



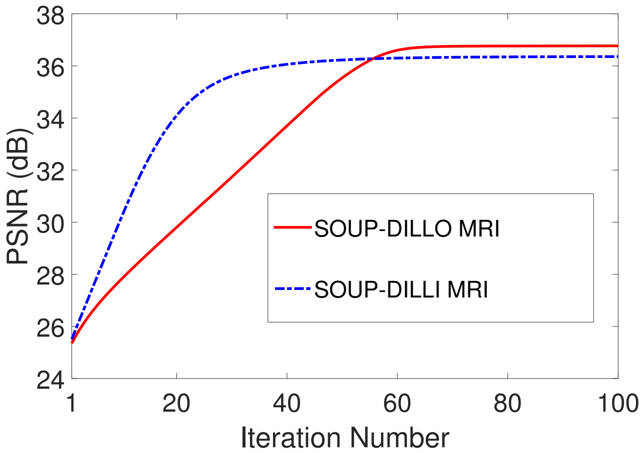
Learned real$\{\boldsymbol{D}\}$



imag$\{\boldsymbol{D}\}$



2D CS MRI results II

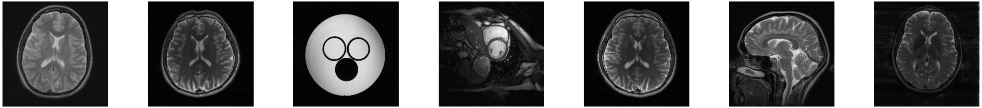


(SNR vs fully sampled image.)
Using $\|\boldsymbol{z}_m\|_0$ leads to higher SNR than $\|\boldsymbol{z}_m\|_1$.
Adaptive case is non-convex anyway...

Matlab code: `http://web.eecs.umich.edu/~fessler/irt/reproduce/`

`https://gitlab.eecs.umich.edu/fessler/soupdil_dinokat`

2D CS MRI results III



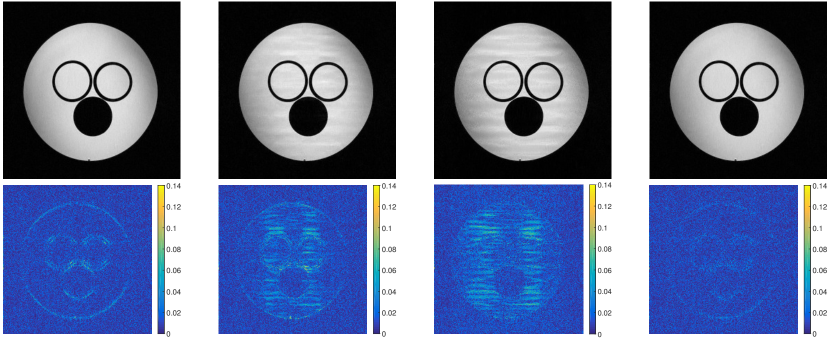
(a) (b) (c) (d) (e) (f) (g)

PSNR:

Im.	Samp.	Acc.	0-fill	Sparse MRI	PANO	DLMRI	SOUP-DILLI	SOUP-DILLO
a	Cart.	7x	27.9	28.6	**31.1**	**31.1**	30.8	**31.1**
b	Cart.	2.5x	27.7	31.6	41.3	40.2	38.5	**42.3**
c	Cart.	2.5x	24.9	29.9	34.8	36.7	36.6	**37.3**
c	Cart.	4x	25.9	28.8	**32.3**	32.1	32.2	**32.3**
d	Cart.	2.5x	29.5	32.1	36.9	38.1	36.7	**38.4**
e	Cart.	2.5x	28.1	31.7	40.0	38.0	37.9	**41.5**
f	2D rand.	5x	26.3	27.4	30.4	30.5	30.3	**30.6**
g	Cart.	2.5x	32.8	39.1	41.6	41.7	42.2	**43.2**
Ref.				[10]	[11]	[1]	[9]	[9]

2D CS MRI results IV

DLMRI PANO FDLCP SOUP-DILLO



[1] [11] [12] [9]

Summary: 2D static MR reconstruction from under-sampled data with adaptive dictionary learning and convergent algorithm, faster than K-SVD approach of DLMRI.

Summary

- Data-driven / adaptive regularization
  - Beneficial for low-dose CT and under-sampled MRI reconstruction
  - Dictionary atom structure (*e.g.*, low rank) further helpful for dynamic MRI
  - Block proximal methods provide reasonably computational efficiency
  - Convergence theory (unlike KSVD)
- Future work:
  - Synthesis (*e.g.*, dictionary) vs analysis (*e.g.*, transform learning) formulations
    Begs for some principled model comparison...
  - Online methods for reduced memory, better adaptation [13–16]
  - Adaptive methods versus "deep" methods?
  - Prospective use

This summer...

June 2018 special issue of IEEE Trans. on Medical Imaging [17]:

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Image Reconstruction Is a New Frontier of Machine Learning

Ge Wang, *Fellow, IEEE*, Jong Chu Ye, *Senior Member, IEEE*, Klaus Mueller, *Senior Member, IEEE*, and Jeffrey A. Fessler, *Fellow, IEEE*

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