Image Denoising and Deblurring

Applied Math 515 Final Project

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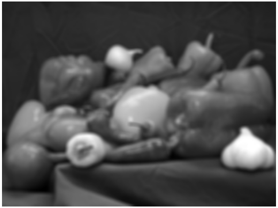
Mathematical Formulation

$$\underset{\text{Blur operator}}{A}\overset{\text{True image}}{x} + \underset{\text{Noise}}{w} = \overset{\text{Observed image}}{b}$$

- Blur: Ax is a discrete convolution of the true image with a Gaussian kernel (reflexive boundary conditions).
- Noise: w is noise drawn from a Gaussian or Student's t distribution.

Naive Solution: $x = A^{-1}b$

True image

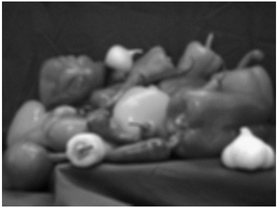


Blurred image

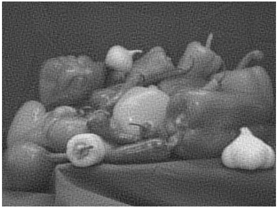
Recovered image

Naive Solution: $x = A^{-1}(b - w)$

True image



Blurred and noisy image



Recovered image

Since the blur operator is ill-conditioned, a better approach is to minimize a regularized loss function.

General Loss Function

$$L_b(x) = \underbrace{f(Ax - b)}_{\text{Fidelity term}} + \underbrace{\lambda R(x)}_{\text{Regularization}}$$

Fidelity Terms

$$f = \begin{cases} \|\cdot\|_F^2 \\ h_\gamma(\cdot) \\ \gamma^{-1}\log(\cosh(\gamma\cdot)) \end{cases}$$

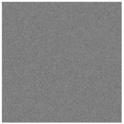
Regularization Terms

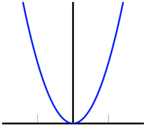
$$R = \begin{cases} \|Wx\|_1 \\ TV(x) \end{cases}$$

Fidelity Term Penalty Functions

The fidelity term $f(Ax - b)$ measures how well our results comply with the linear blurring model. Depending upon the type of noise present in the observed image, the choice of penalty function may influence the efficacy of our deblurring/denoising procedure.

Gaussian Noise

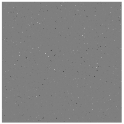


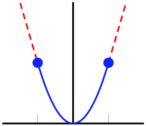


Due to the lack of outliers, the quadratic penalty is sufficient

$$f(z) = \frac{1}{2}\|z\|^2$$

Student's t Noise



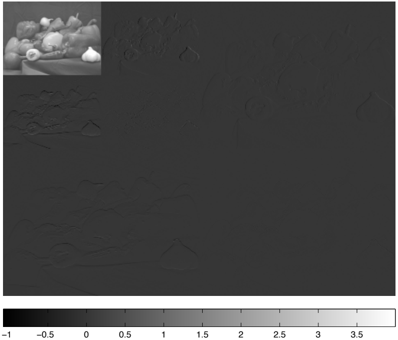


Huber penalty preferred since it is more robust to heavy-tailed noise

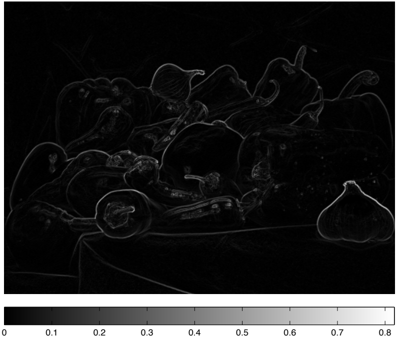
$$f(z) = \min_y \frac{1}{2}\|z - y\|^2 + \gamma\|y\|_1$$

Image Assumptions and Regularizers

2-Level Haar Transform



$\left|x_{ij} - x_{i+1,j}\right| + \left|x_{ij} - x_{i,j+1}\right|$



Our choices of regularizers assume that images are sparse in wavelet domains and that they are relatively smooth (low total variation). SPLIT THIS INTO 2 SLIDES

L1 Wavelet Regularization

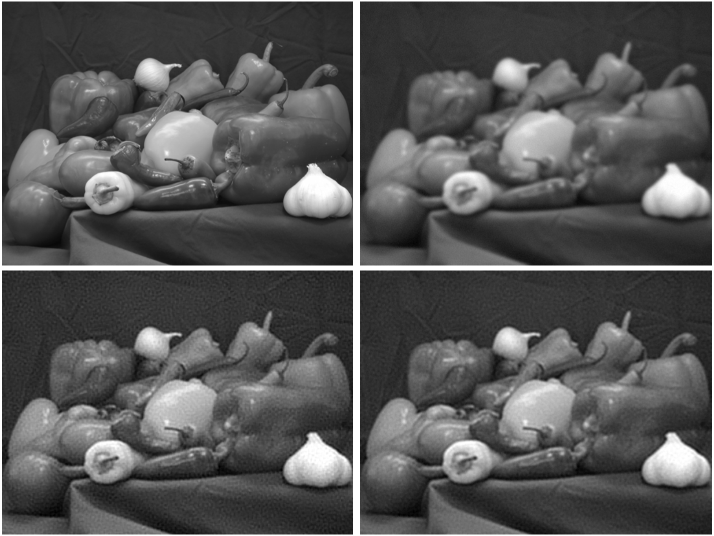
Loss Function

$$L_b(x) = f(Ax - b) + \lambda \|Wx\|_1$$

Proximal Gradient Step

$$x^{k+1} = \mathrm{prox}_{\alpha^{-1}\lambda\|W\cdot\|_1}\left(x^k - \alpha^{-1}A^T \nabla f(Ax^k - b)\right)$$

Results: Gaussian Noise



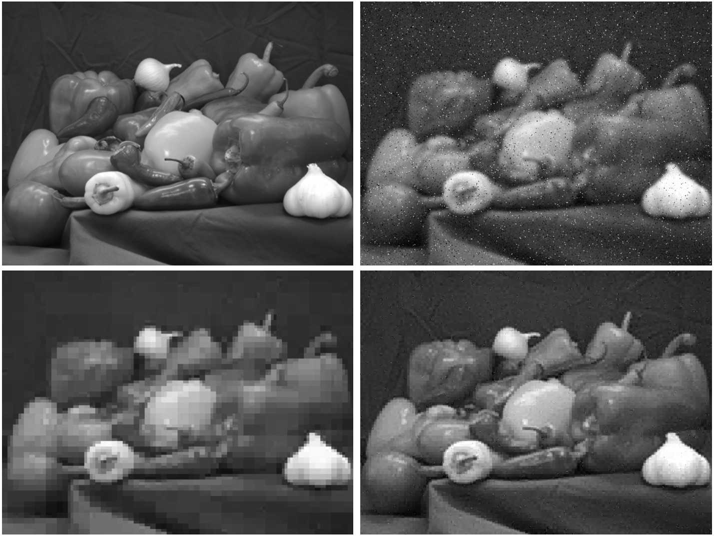
Original Image

Blurred and Noisy

Frobenius Loss

Huber Loss

Results: Student's t Noise



Original Image

Blurred and Noisy

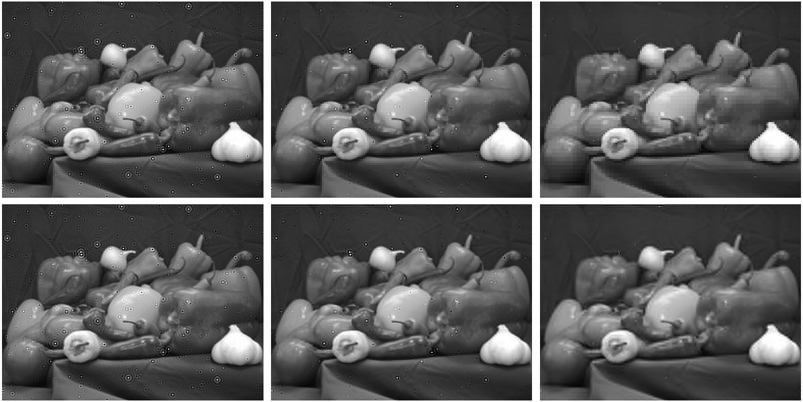
Frobenius Loss

Huber Loss

Choosing λ

Haar

Daubechies



$\lambda = 10^{-4}$ $\lambda = 10^{-3}$ $\lambda = 10^{-2}$

Total Variation Regularization

Loss Function

$$L_b(x) = f(Ax - b) + \lambda \mathrm{TV}(x) + \delta(x|[0,1])$$

Proximal Gradient Step

$$x^{k+1} = \text{prox}_{\alpha^{-1}(\lambda\|\cdot\|_{TV} + \delta_{[0,1]})}(\underbrace{x^k - \alpha^{-1}A^T \nabla f(Ax^k - b)}_{u^k})$$

$$= \underset{z}{arg\,min}\left(\|u^k - z\|_F^2 + \alpha^{-1}\lambda\|z\|_{TV} + \delta(z|[0,1])\right)$$

$$= P_{[0,1]}\left(\underset{z}{arg\,min}\left(\|u^k - z\|_F^2 + \alpha^{-1}\lambda\|z\|_{TV}\right)\right)$$

Dual Form of Total Variation

A Few Definitions

- $\mathcal{P} = \{(p,q) \in \mathbb{R}^{(m-1)\times n} \times \mathbb{R}^{m\times(n-1)} : |p_{i,j}| \leq 1, |p_{i,j}| \leq 1\}$,
- $\mathcal{L} : \mathbb{R}^{(m-1)\times n} \times \mathbb{R}^{m\times(n-1)} \to \mathbb{R}^{m\times n}$ such that

$$\mathcal{L}(p,q)_{i,j} = p_{i,j} + q_{i,j} - p_{i-1,j} - q_{i,j-1}$$

  for $i = 1,\ldots,m$, $j = 1,\ldots,n$, and
  $p_{0,j} = p_{m,j} = q_{i,0} = q_{i,n} = 0$.
- P_C is the usual projection operator onto the set C

Total Variation

$\mathrm{TV}(x) = max_{p,q\in\mathcal{P}} T(x,p,q) \implies T(x,p,q) = \mathrm{Tr}(\mathcal{L}(p,q)^T x)$.

Dual Form of TV Denoising with $\|\cdot\|_F^2$

The problem:

$$\min_{x\in C}\|x-b\|_F^2+2\lambda\mathrm{TV}(x),\, C=[0,1]$$

Dual problem:

$$\min_{(p,q)\in\mathcal{P}}\underbrace{-\|H_C(b-\lambda\mathcal{L}(p,q))\|_F^2+\|b-\lambda\mathcal{L}(p,q)\|_F^2}_{h(p,q)}$$

$$H_C(x)=\underbrace{x-P_C(x)}_{\mathrm{prox}}$$

Optimality conditions:

$$x=P_C(b-\lambda\mathcal{L}(p,q)).$$

Optimization of Dual Form

Problem Statement

$$\min_{(p,q)\in\mathcal{P}} \left\{ \|b - \lambda\mathcal{L}(p,q)\|_F^2 - \|(I - P_{[0,1]})(b - \lambda\mathcal{L}(p,q))\|_F^2 \right\}$$

$$\min_{(p,q)} \left\{ \underbrace{\|b - \lambda\mathcal{L}(p,q)\|_F^2 - \|(I - P_{[0,1]})(b - \lambda\mathcal{L}(p,q))\|_F^2}_{=h(p,q)} + \delta((p,q)|\mathcal{P}) \right\}$$

$$\nabla h(p,q) = -2\lambda\mathcal{L}^T P_{[0,1]}(b - \lambda\mathcal{L}(p,q))$$

Lipschitz with constant $\leq 16\lambda^2$

$\Rightarrow$ Use projected gradient

Optimization in Dual Form

Projection onto $\mathcal{P}$

Recal $\mathcal{P} = (p, q) \in [-1, 1]^{m-1 \times n} \times [-1, 1]^{m \times n-1}$

$$P_{\mathcal{P}}(p, q) = (r, s) \text{ with } \begin{cases} r_{ij} = sgn(p_{ij}) \min\{1, |p_{ij}|\} \\ s_{ij} = sgn(q_{ij}) \min\{1, |q_{ij}|\} \end{cases}$$

Projected Gradient Step

$$(p^{k+1}, q^{k+1}) = P_{\mathcal{P}} \left((p^k, q^k) + \frac{1}{8\lambda} \mathcal{L}^T P_{[0,1]}(b - \lambda \mathcal{L}(p, q)) \right)$$

Monotone FISTA TV Regularization

MFISTA(b, f, λ)

$y^1 = x^0 = b;\ t^1 = 1$

$\alpha \geq Lip(\nabla f)$

for $k = 1 : N$ **do**

$$u^k = y^k - \frac{A^T \nabla f(Ay^k - b)}{\alpha}$$

$$z^k = FGP(u^k, \tfrac{\lambda}{2\alpha})$$

$$x^k = \underset{x \in \{x^{k-1}, z^k\}}{\text{argmin}} L_b(x)$$

$$t^{k+1} = \frac{1+\sqrt{1+4{t^k}^2}}{2}$$

$$y^{k+1} = x^k + \frac{t^k}{t^{k+1}}(z^k - x^k) + \frac{t^k-1}{t^{k+1}}(z^k - x^k)$$

end for

return x^N

FGP(b, λ)

$(r^1_{ij}, s^1_{ij}) = (p^0_{ij}, q^0_{ij}) = 0;\ t^1 = 1$

for $k = 1 : N$ **do**

$$(p^k, q^k) = P_{\mathcal{P}}\left((r^k, s^k) - \frac{\mathcal{L}^T P_{[0,1]}(b - \lambda \mathcal{L}(r^k, s^k))}{8\lambda}\right)$$

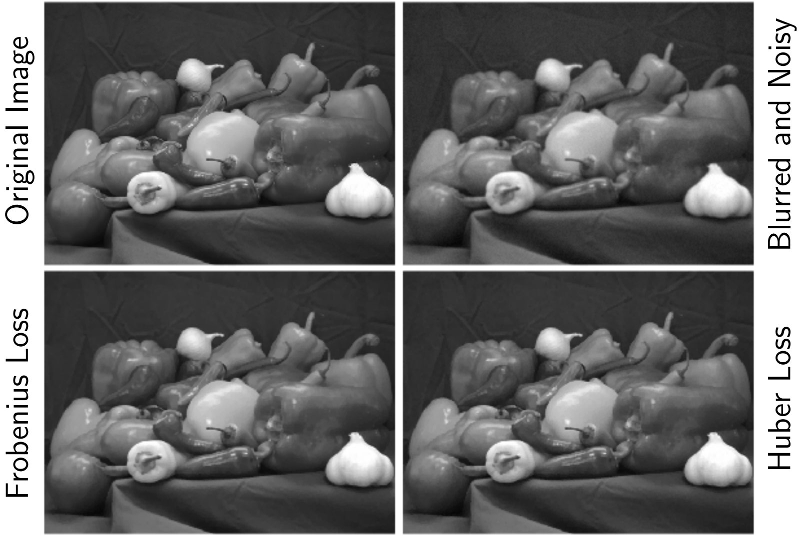
$$t^{k+1} = \frac{1+\sqrt{1+4{t^k}^2}}{2}$$

$$(r^k, s^k) = (p^k, q^k) + \frac{t^k-1}{t^{k+1}}(p^k - p^{k-1}, q^k - q^{k-1})$$

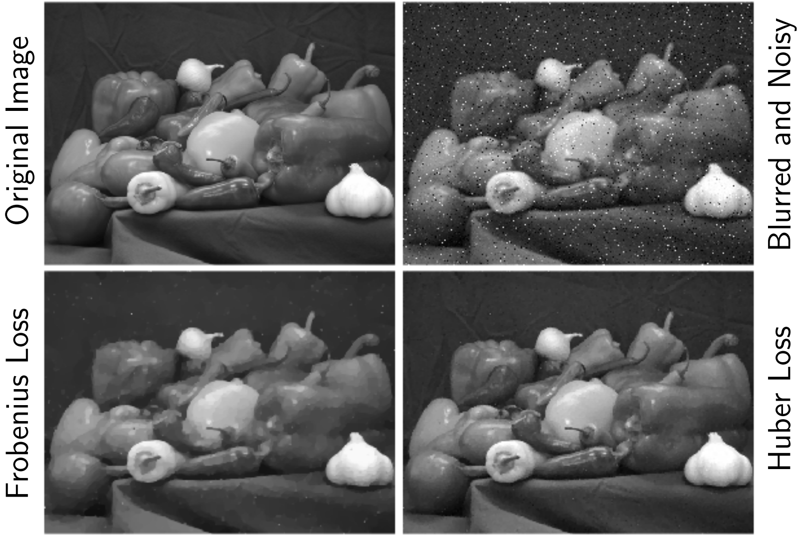
end for

return $P_{[0,1]}(b - \lambda \mathcal{L}(p^N, q^N))$

Results: Gaussian Noise



Results: Student's t Noise



Conclusions

Wavelet vs. Total Variation

- Total variation seems to do better for high amounts of noise.
- **How do they compare on timing???? Any advantages of Wavelet???**

Frobenius vs Huber

- On Gaussian noise, the two are comparable.
- Huber outperforms Frobenius on noise with heavier tail.

Challenges

- Ideal parameter values change image to image.
- How can we quantitatively evaluate performance?
- How can we optimize parameters without performance metric?

Questions?

- Kelsey's book
- Beck, A., Teboulle, M. (2009) *IEEE Trans. on Image Proc.* 18(11):2419-2434
- article on wavelet fista