

Nonlinear Filtering

- Linear filters
 - Tend to blur edges and other image detail.
 - Perform poorly with non-Gaussian noise.
 - Result from Gaussian image and noise assumptions.
 - Images are not Gaussian.
- Nonlinear filter
 - Can preserve edges
 - Very effective at removing impulsive noise
 - Result from non-Gaussian image and noise assumptions.
 - Can be difficult to design.

Linear Filters

- Definition: A system $y = T[x]$ is said to be linear if for all $\alpha, \beta \in \mathbb{R}$

$$\alpha y_1 + \beta y_2 = T[\alpha x_1 + \beta x_2]$$

where $y_1 = T[x_1]$ and $y_2 = T[x_2]$.

- Any filter of the form

$$y_s = \sum_r h_{s,r} x_r$$

Homogeneous Filters

- Definition: A filter $y = T[x]$ is said to be homogeneous if for all $\alpha \in \mathbb{R}$

$$\alpha y = T[\alpha x]$$

- This is much weaker than linearity.
- Homogeneity is a natural condition for scale invariant systems.

Median Filter

- Let W be a window with an odd number of points.
- Then the median filter is given by

$$y_s = \text{median} \{x_{s+r} : r \in W\}$$

- Is the median filter:
 - Linear?
 - Homogeneous?
- Consider the 1-D median filter with a 3-point window.

| | | | | | | | | |
|------|---|---|---|-------|---|---|---|---|
| x(m) | 0 | 0 | 1 | 1,000 | 1 | 1 | 2 | 2 |
| y(m) | ? | 0 | 1 | 1 | 1 | 1 | 2 | ? |

Median Filter: Optimization Viewpoint

- Consider the median filter

$$y_s = \text{median} \{x_{s+r} : r \in W\}$$

and consider the following functional.

$$F_s(\theta) \triangleq \sum_{r \in W} |\theta - x_{s+r}|$$

- Then y_s solves the following optimization equation.

$$y_s = \arg \min_{\theta} F_s(\theta)$$

- Differentiating, we have

$$\begin{aligned} \frac{d}{d\theta} F(\theta) &= \frac{d}{d\theta} \sum_{r \in W} |\theta - x_{s+r}| \\ &= \sum_{r \in W} \text{sign}(\theta - x_{s+r}) \\ &\triangleq f(\theta) \end{aligned}$$

This expression only holds for $\theta \neq x_{s+r}$ for all $r \in W$.

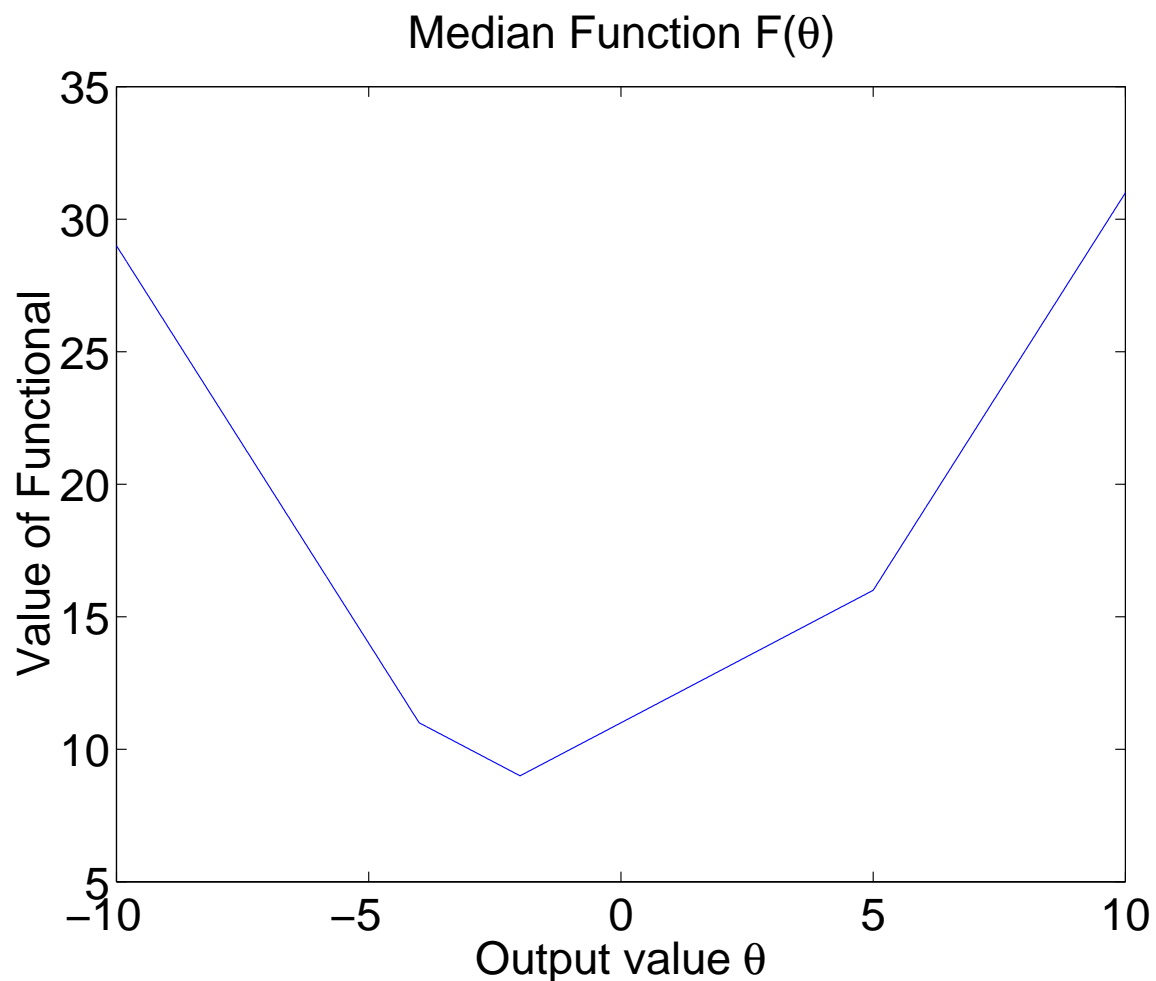
- So the solution falls at $\theta = x_{s*}$ such that

$$0 = \sum_{\substack{r \in W \\ r \neq (s*-s)}} \text{sign}(\theta - x_{s+r})$$

Example: Median Filter Function

- Consider a 1-D median filter
 - Three point window of $W = \{-1, 0, 1\}$
 - Inputs $[x(n-1), x(n), x(n+1)] = [-2, -4, 5]$.

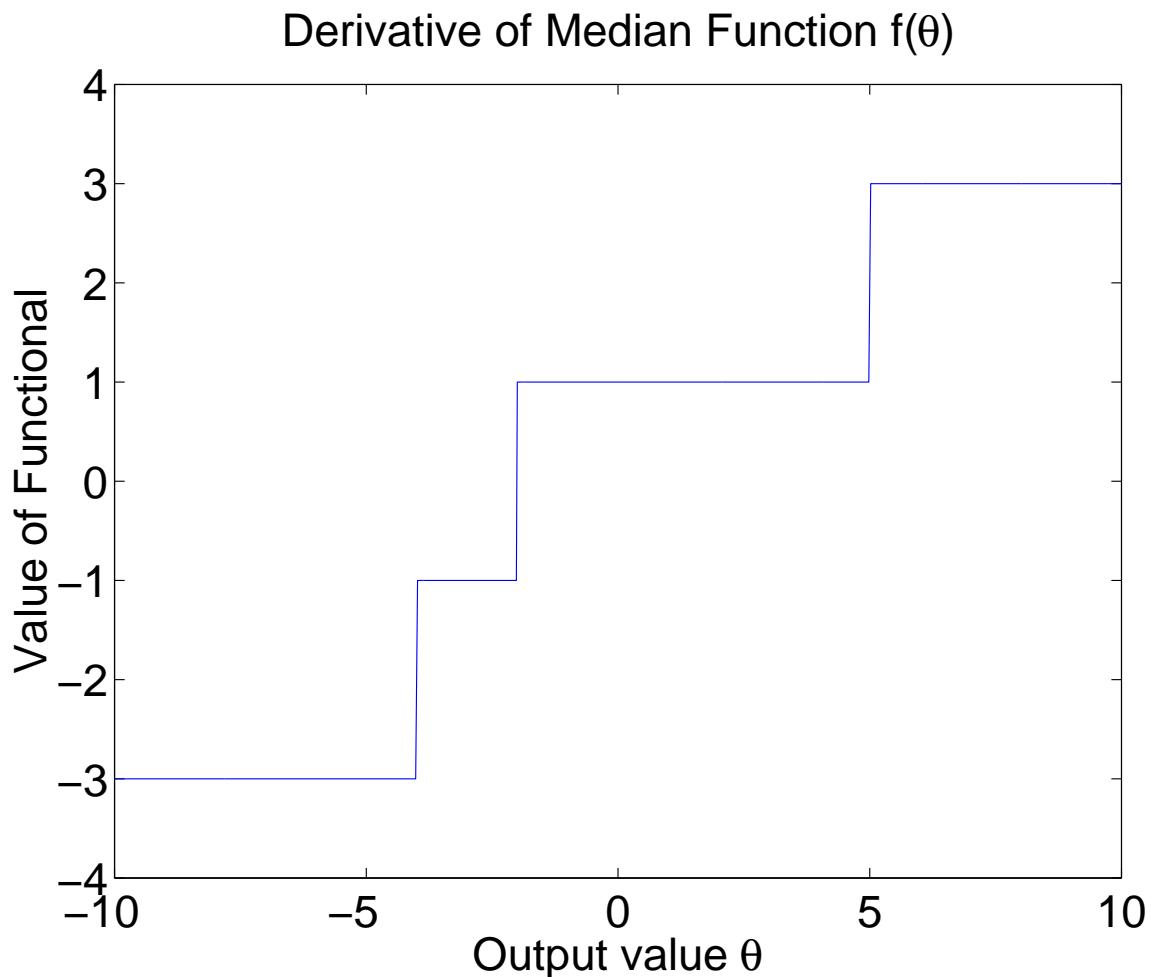
$$F(\theta) = \sum_{k=-1}^1 |\theta - x_{n+k}|$$



Example: Derivative of Median Filter Function

- Consider a 1-D median filter
 - Three point window of $W = \{-1, 0, 1\}$
 - Inputs $[x(n-1), x(n), x(n+1)] = [-2, -4, 5]$.

$$f(\theta) = \sum_{k=-1}^1 \text{sign}(\theta - x_{n+k})$$

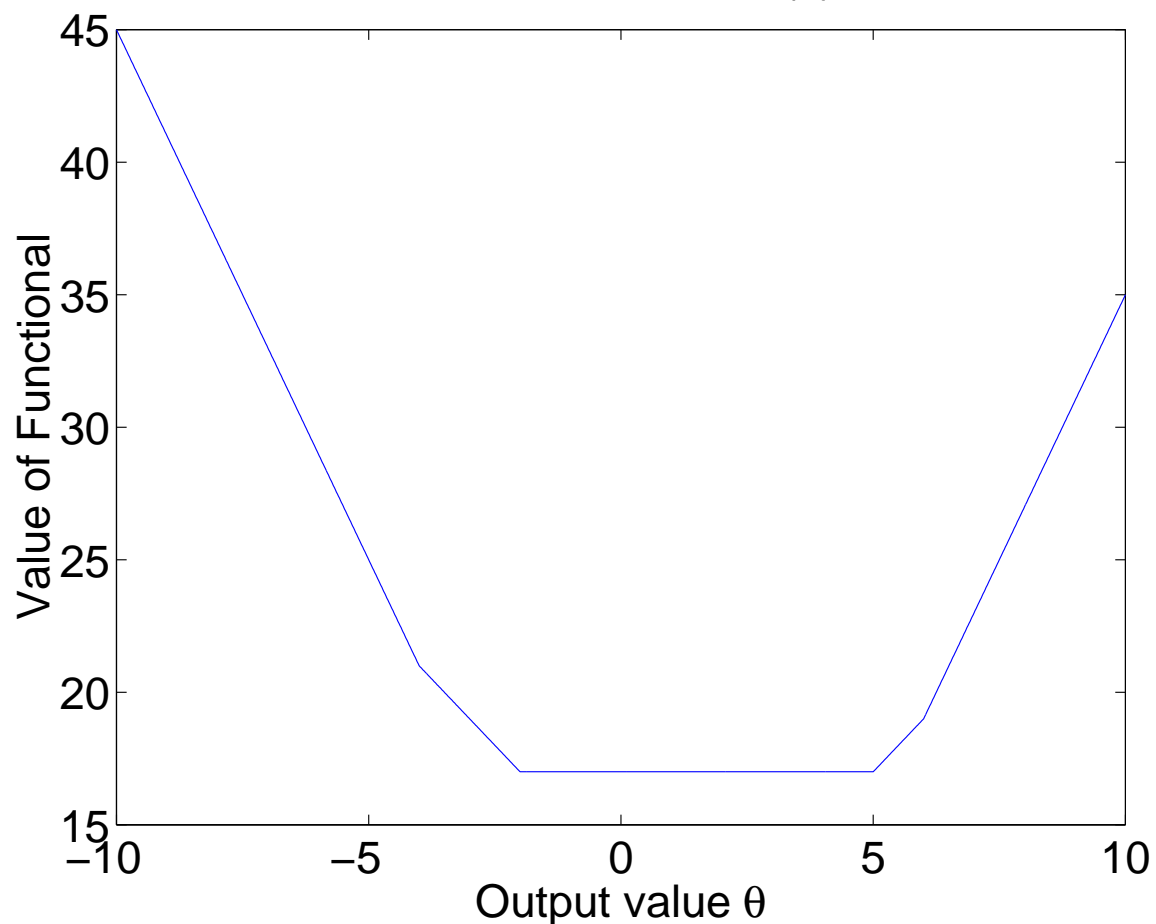


Problem with an Even Number of Points

- Consider a 1-D median filter
 - Four point window of $W = \{-1, 0, 1, 2\}$
 - Inputs $[x(n-1), x(n), x(n+1), x(n+2)] = [-2, -4, 5, 6]$.
- Solution is not unique.

$$F(\theta) = \sum_{k=-1}^2 |\theta - x_{n+k}|$$

Median Function $F(\theta)$



Weighted Median Filter

- Defined the functional

$$F(\theta) \triangleq \sum_{r \in W} a_r |\theta - x_{s+r}|$$

where a_r are weights assigned to each point in the window W .

- Weighted median is computed by

$$y_s = \arg \min_{\theta} \sum_{r \in W} a_r |\theta - x_{s+r}|$$

- Differentiating, we have

$$\begin{aligned} \frac{d}{d\theta} F(\theta) &= \frac{d}{d\theta} \sum_{r \in W} a_r |\theta - x_{s+r}| \\ &= \sum_{r \in W} a_r \text{sign}(\theta - x_{s+r}) \\ &\triangleq f(\theta) \end{aligned}$$

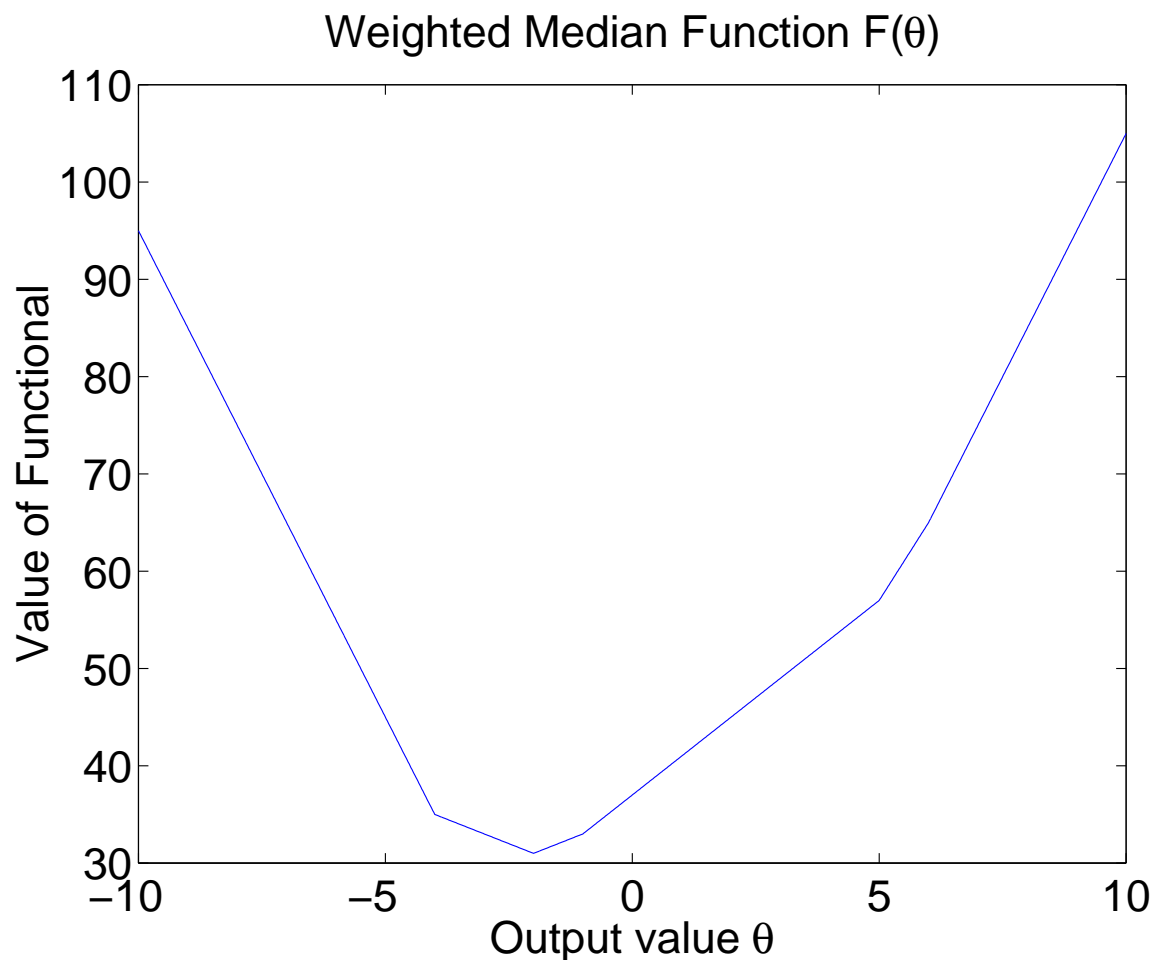
This expression only holds for $\theta \neq x_r$ for all $r \in W$.

- Need to find s^* such that $f(\theta)$ is “nearly” zero.

Example: Weighted Median Filter Function

- Consider a 1-D median filter
 - Five point window of $W = \{-2, -1, 0, 1, 2\}$
 - Inputs $[x(n-2), \dots, x(n+2)] = [6, -2, -4, 5, -1]$.
 - Weights $[a(-2), a(-1), a(0), a(1), a(2)] = [1, 2, 4, 2, 1]$.

$$F(\theta) = \sum_{k=-1}^1 a(k) |\theta - x_{n+k}|$$

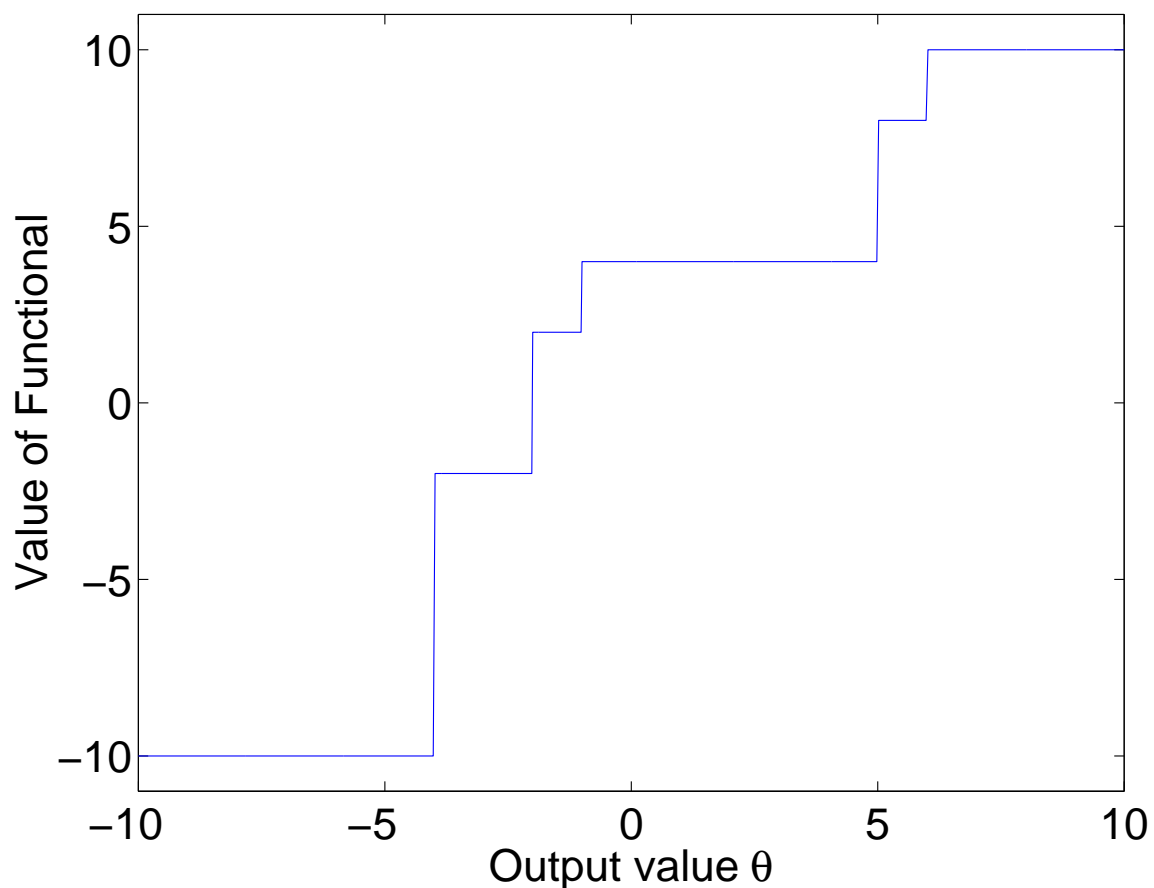


Example: Derivative of Median Filter Function

- Consider a 1-D median filter
 - Five point window of $W = \{-2, -1, 0, 1, 2\}$
 - Inputs $[x(n-2), \dots, x(n+2)] = [6, -2, -4, 5, -1]$.
 - Weights $[a(-2), a(-1), a(0), a(1), a(2)] = [1, 2, 4, 2, 1]$.

$$f(\theta) = \sum_{k=-1}^1 a(k) \operatorname{sign}(\theta - x_{n+k})$$

Derivative of Weighted Median Function $f(\theta)$



Computation of Weighted Median

1. Sort points in window.

- Let $x_{(1)} \leq x_{(2)} \leq \dots \leq x_{(p)}$ be the sorted values.
- These values are known as order statistics.
- Let $a_{(1)}, a_{(2)}, \dots, a_{(p)}$ be the **corresponding** weights.

2. Find i^* such that the following equations hold

$$a_{i^*} + \sum_{i=1}^{i^*-1} a_{(i)} \geq \sum_{i=i^*+1}^p a_{(i)}$$

$$\sum_{i=1}^{i^*-1} a_{(i)} \leq \sum_{i=i^*+1}^p a_{(i)} + a_{i^*}$$

3. Then the value $x_{(i^*)}$ is the weighted median value.

Comments on Weighted Median Filter

- Weights may be adjusted to yield the “best” filter.
- Largest and smallest values are ignored.
- Same as median filter for $a_r = 1$.