EECS 4422/5323

Unit 7: Spatiotemporal analysis

Outline

- Introduction
- Orientation in visual space-time
- A representation for spatiotemporal patterns
- Spatiotemporal boundaries
- A framework for spatiotemporal analysis
- Applications
- Summary

Introduction

- We have considered the analysis of spatial structure.
  - Oriented, bandpass representations.
- We have considered analysis of the temporal dimension
  - Motion
- Now we consider the integrated analysis and interpretation of the spatial and temporal dimensions.
  - Spatiotemporal analysis

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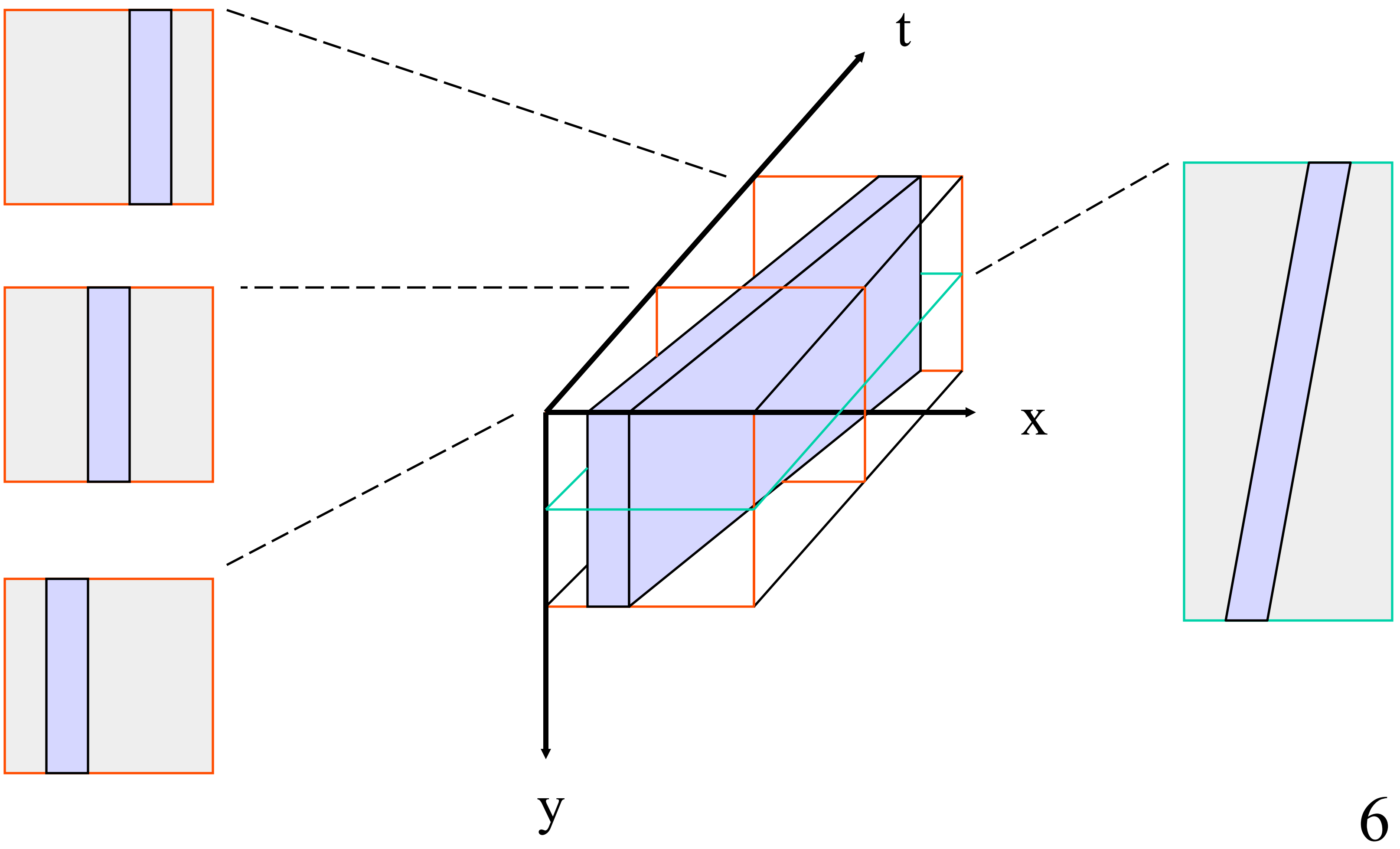
Orientation in visual space-time: Basics

- The local orientation (or lack thereof) of a pattern is one of its most salient characteristics.
- Geometrically, orientation captures the local first-order structure of a pattern.
- For vision, local spatiotemporal orientation can have additional interpretations.
  - Image velocity is manifest as spatiotemporal orientation.
  - And more...

Orientation in visual space-time: Graphic

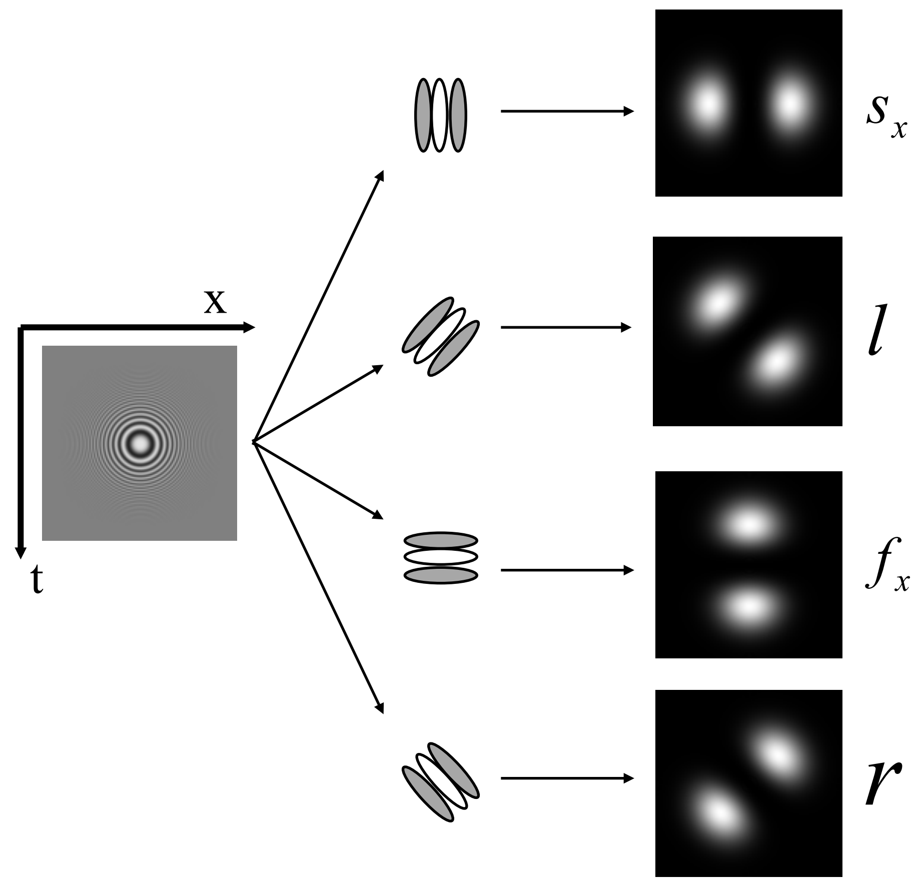


Orientation in visual space-time: Representation

- Goal is to analyze spatiotemporal data according to its local orientation structure.
  - Consider orientation in x-t and y-t planes, with local weighted averaging in orthogonal spatial dimension.
  - Filter for multiple bands each tuned for certain orientations in a spatiotemporal plane.
  - For example, select 4 orientations/plane: horizontal, vertical, 2 diagonals
- Consider single spatiotemporal scale (for now).

Orientation in visual space-time: Filtering

- Apply filters tuned to 4 different orientations in both x-t and y-t domains.
- In general, might consider additional directions.
- Filter specifics:
  - Oriented bandpass filters in spatiotemporal slice.
  - Lowpass filter in orthogonal spatial dimension.
  - Pointwise squared to yield local “oriented energy”.



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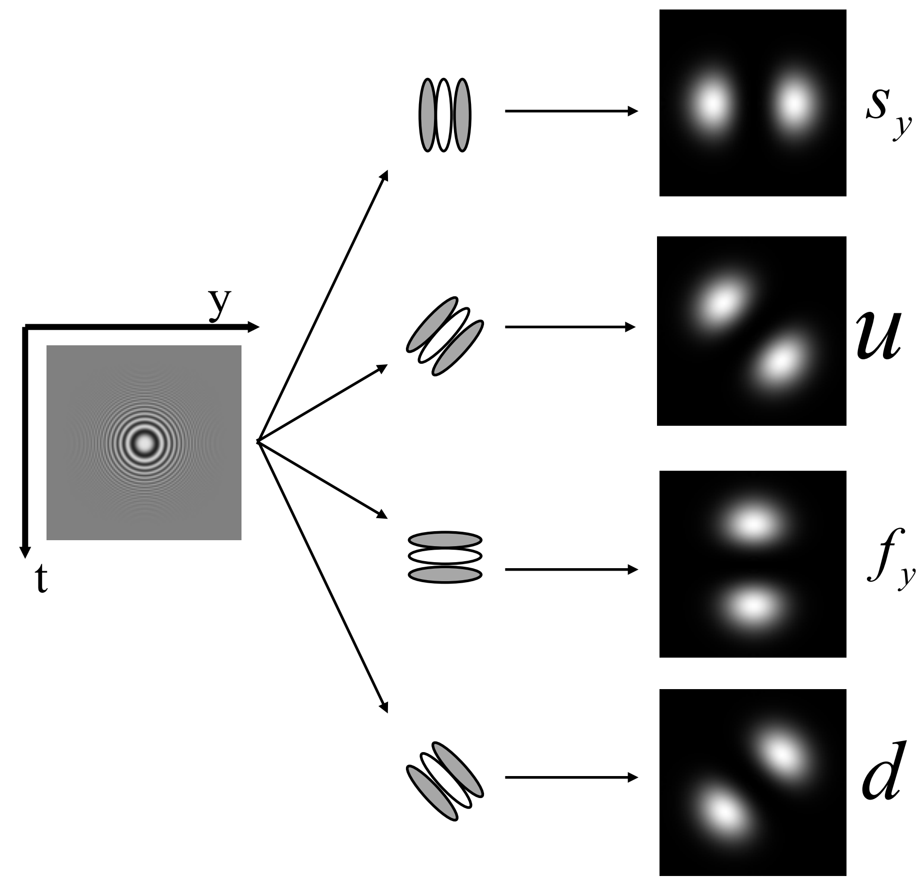


Orientation in visual space-time: Normalization

- For any given orientation, the filter response is a joint function of
  - orientation
  - contrast

- Normalization yields purer measure of orientation

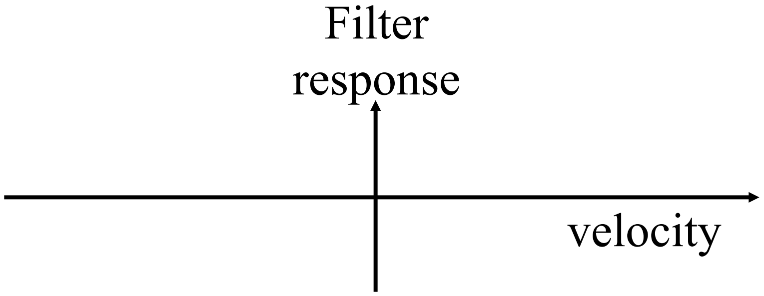
$$R(x,y,t)=\frac{r(x,y,t)}{r(x,y,t)+l(x,y,t)+s_x(x,y,t)+f_x(x,y,t)+\varepsilon}$$

with ɜ a small bias added for stability.

- Similarly for l , s_x , f_x and their y-t counterparts.

Orientation in visual space-time: Velocity

- Consider the response to a horizontally moving pattern of *r, l* and *s* filters.



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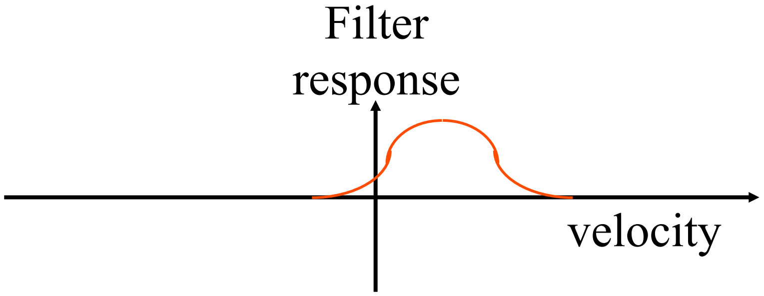

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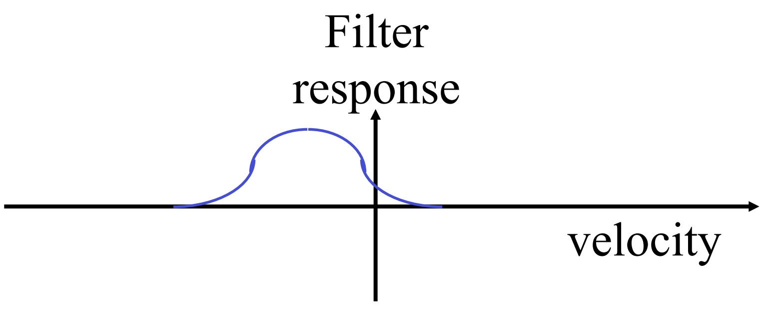

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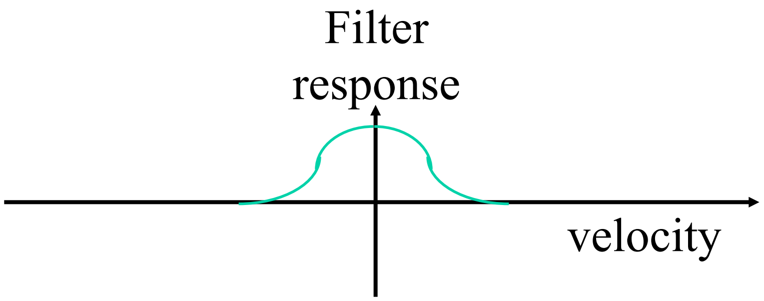

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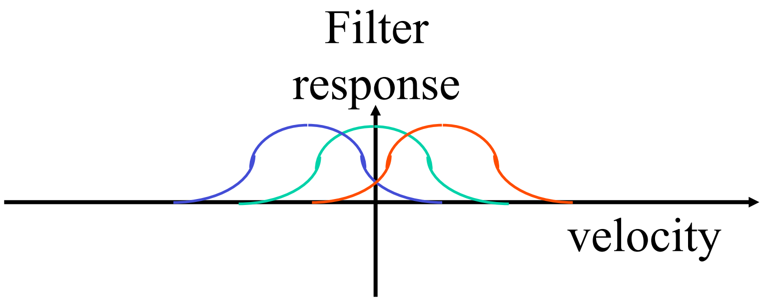

Orientation in visual space-time: Velocity

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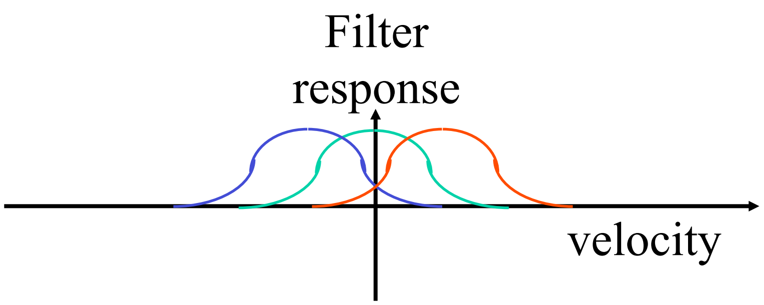
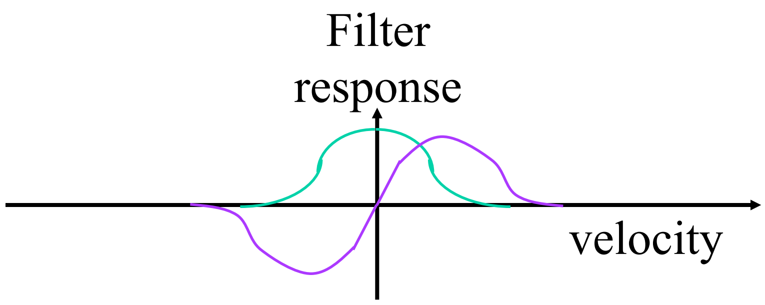
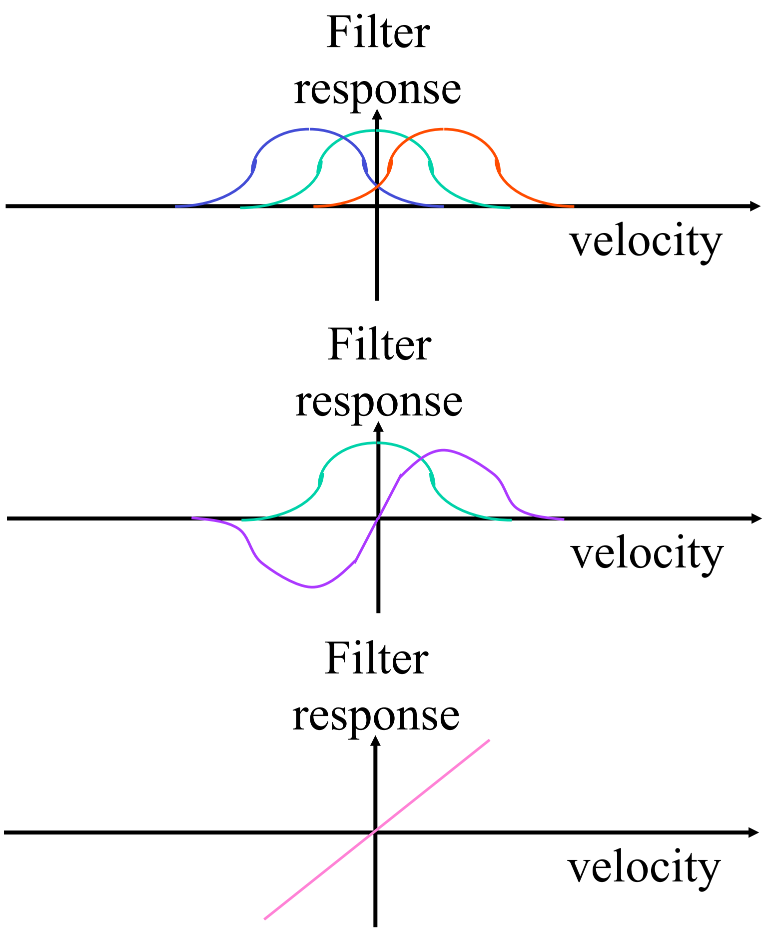
- By taking the difference *r*-*l* we get a single response that is properly signed WRT velocity.





Orientation in visual space-time: Velocity

- Consider the response to a horizontally moving pattern of *r*, *l* and *s* filters.
- By taking the difference *r-l* we get a single response that is properly signed WRT velocity.
- Dividing to get *(r-l)/s* yields a response that is (approximately) linear with velocity.



Orientation in visual space-time: Velocity

Comparison with optical flow constraint equation (OFCE)

- Recall the OFCE as derived from constant brightness assumption

$$E_x u + E_y v + E_t = 0$$

Orientation in visual space-time: Velocity

Comparison with optical flow constraint equation (OFCE)

- Recall the OFCE as derived from constant brightness assumption

$$E_x u + E_y v + E_t = 0$$

- Let us restrict consideration to one spatial dimension + time

$$E_x u + E_t = 0$$

- Now, we can directly solve for (1D) velocity

$$u = -E_t / E_x$$

Orientation in visual space-time: Velocity

Comparison with optical flow constraint equation (OFCE)

- In contrast, let us consider simple differential filters for leftward and rightward movement

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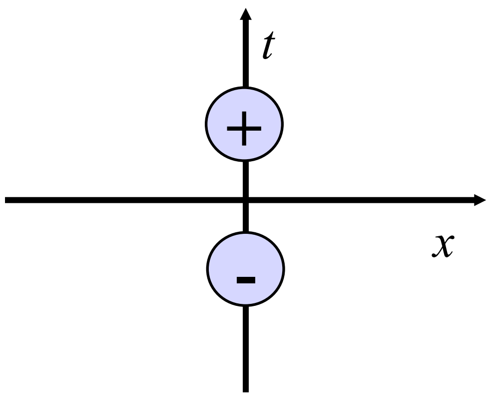

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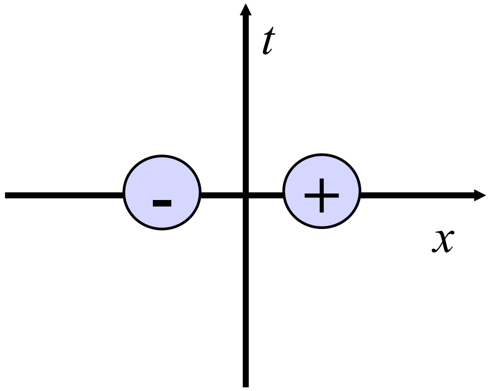

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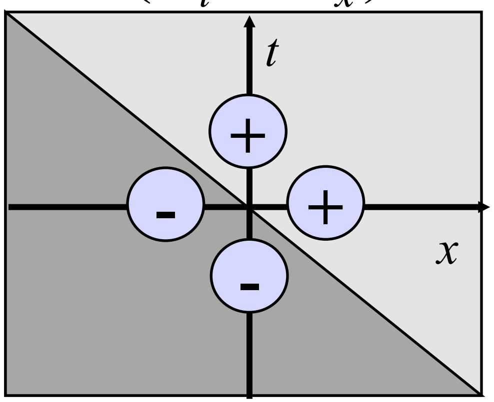

Orientation in visual space-time: Velocity

Comparison with optical flow constraint equation (OFCE)

- In contrast, let us consider simple differential filters for leftward and rightward movement

$$\tilde{l} = (E_t + E_x)/2$$

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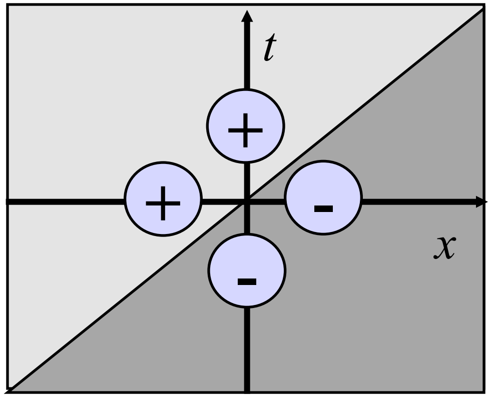

Orientation in visual space-time: Velocity

Comparison with optical flow constraint equation (OFCE)

- In contrast, let us consider simple differential filters for leftward and rightward movement

$$\tilde{l} = (E_t + E_x)/2 \qquad \tilde{r} = (E_t - E_x)/2$$

- Indeed, as we are concerned not with sign for a given direction, but rather magnitude, it suffices to consider the squared filter responses

$$l = (E_t^2 + 2E_xE_t + E_x^2)/4 \qquad r = (E_t^2 - 2E_xE_t + E_x^2)/4$$

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- Finally, to avoid being biased by locally large values of image contrast, we divide through by the square of a first-order measure of local contrast $s = E_x^2$

$$(r - l)/s = -E_t/E_x$$

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$$(r - l)/s = -E_t / E_x$$

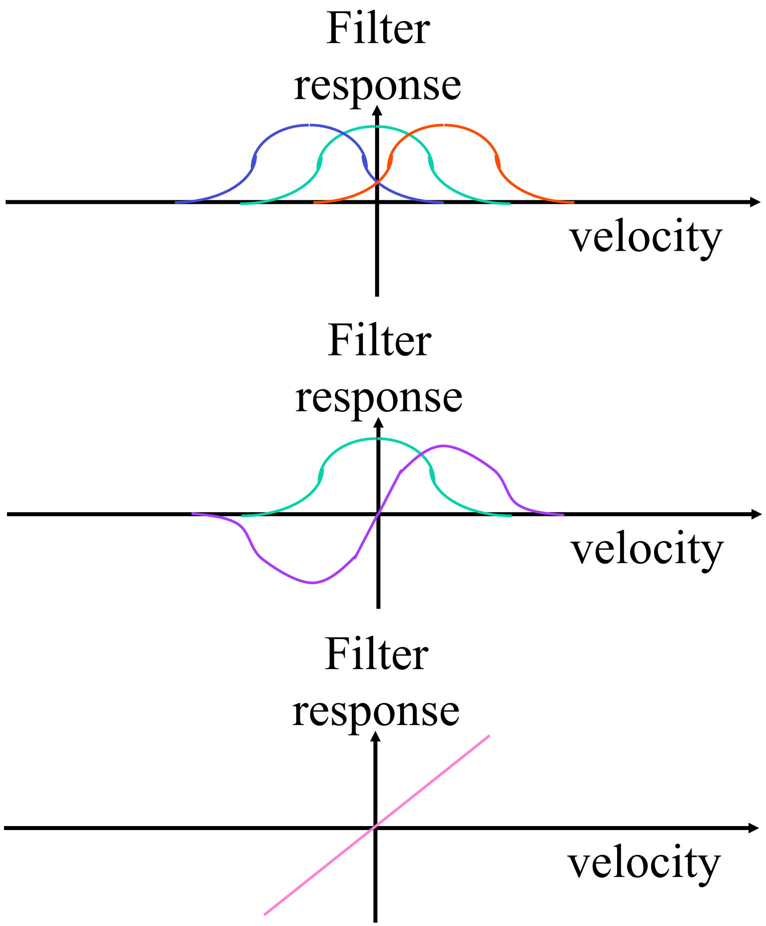
- We now recognize that this computation of velocity is equivalent to that based on the OFCE

$$E_xu + E_t = 0 \Rightarrow u = -E_t / E_x$$

Orientation in visual space-time: Velocity

Conclusion

- Oriented filters in visual space-time support the recovery of image velocity, along a particular direction.
- A “bank” of such filters can be used to span direction and provide an approach to optical flow estimation.



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A representation for spatiotemporal patterns: Motivation

- When confronted with spatiotemporal data, an intelligent system can be overwhelmed by sheer quantity.
- An initial organization would be a key enabler for dealing effectively with data of this nature.
- The organization should afford distinctions that can guide subsequent processing.
- Distinctions that go beyond that of simple velocity.

A representation for spatiotemporal patterns: General approach

- Parse stream of spatiotemporal data into primitive, yet semantically meaningful categories at the earliest stages of processing.

- Make distinctions along the following lines
  - What is moving and what is stationary?
  - Are the moving objects behaving coherently?
  - How much of the variance in the data is due to temporal brightness change?
  - Which portions of the data are simply too unstructured to support further analysis?

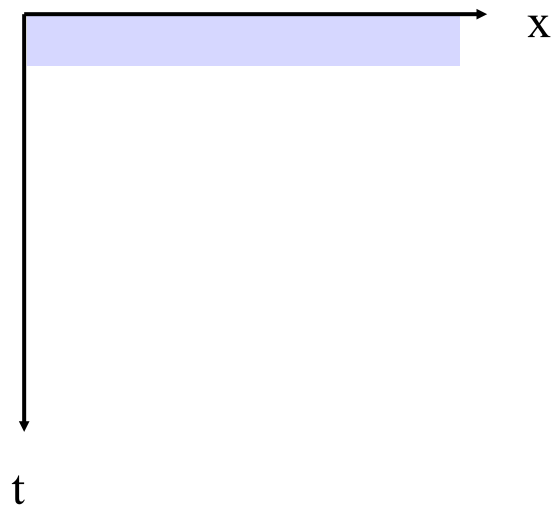
A representation for spatiotemporal patterns: General approach

- Integrate information across both the spatial and temporal dimensions.

- Build on analysis of local orientation.
  - The simplest non-trivial characterization of local geometric structure.

A representation for spatiotemporal patterns: Primitive patterns

- Consider a spatiotemporal slice
  - As an observer views a uniform pattern



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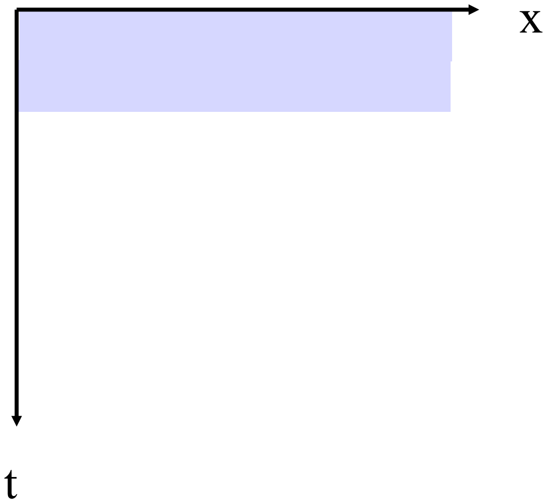

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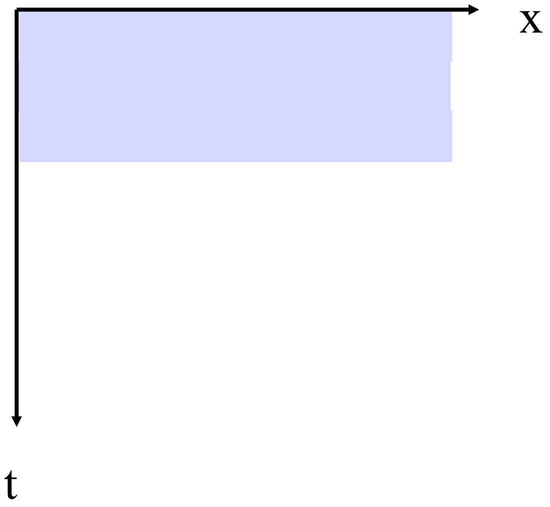

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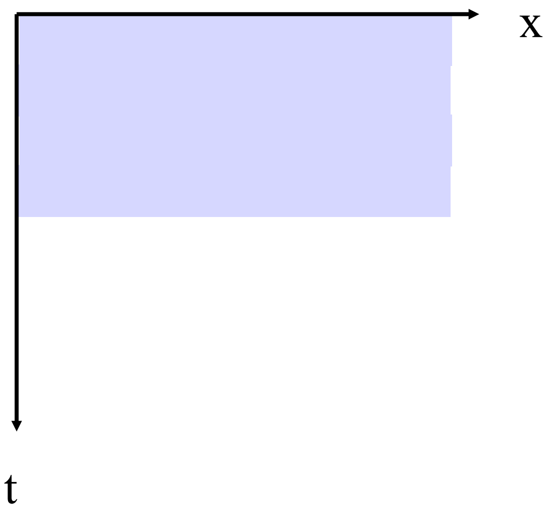

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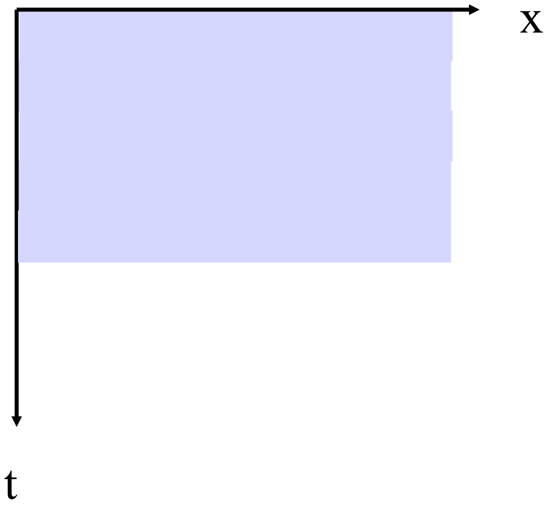

A representation for spatiotemporal patterns: Primitive patterns

- Consider a spatiotemporal slice
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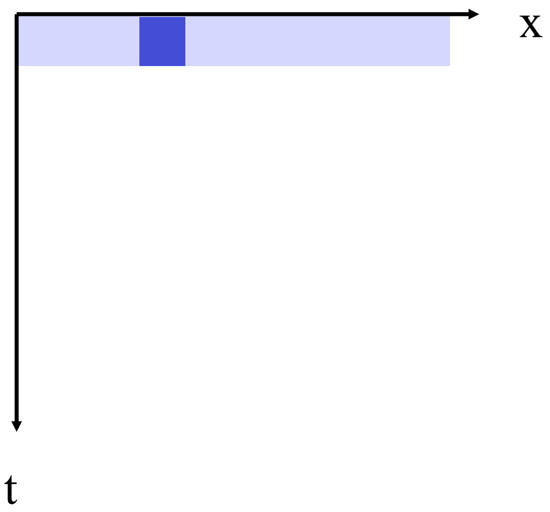

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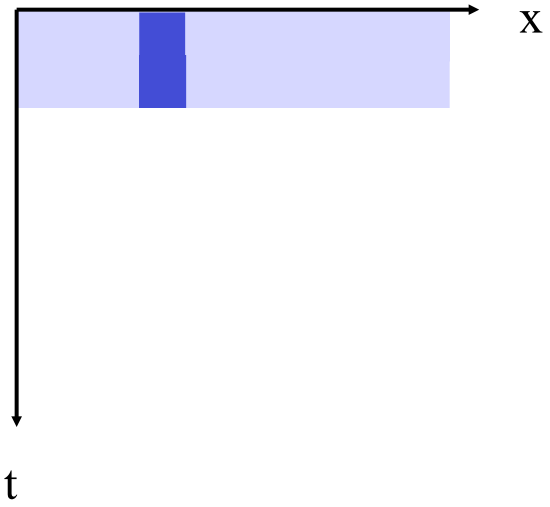

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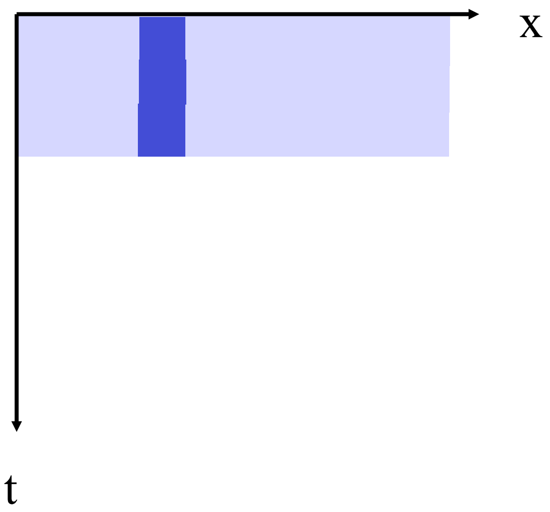

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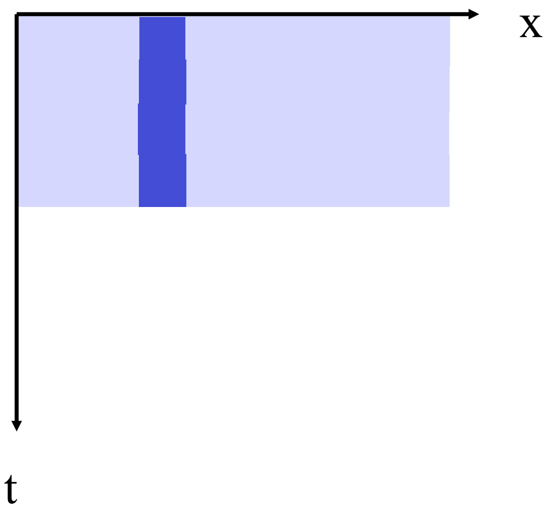

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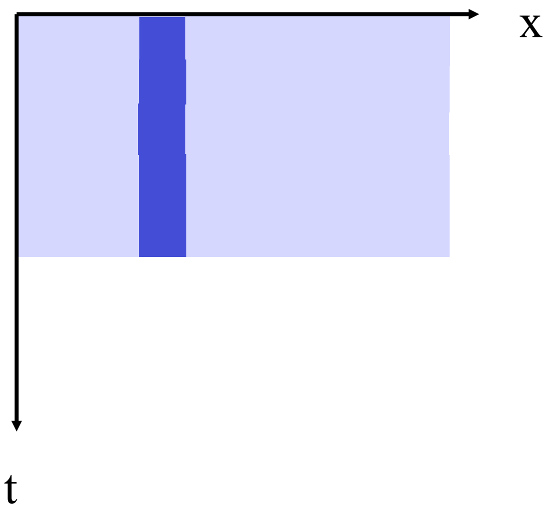

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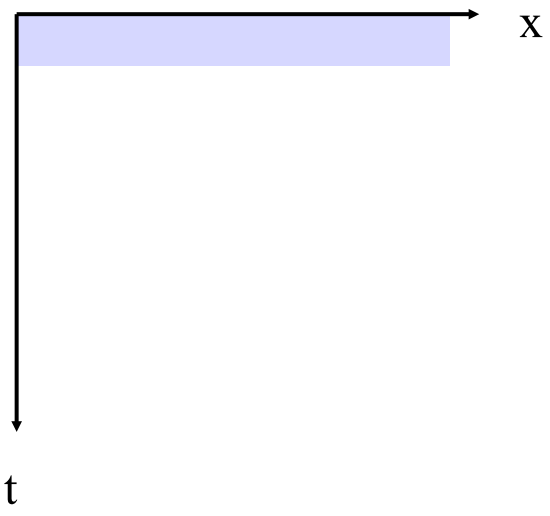

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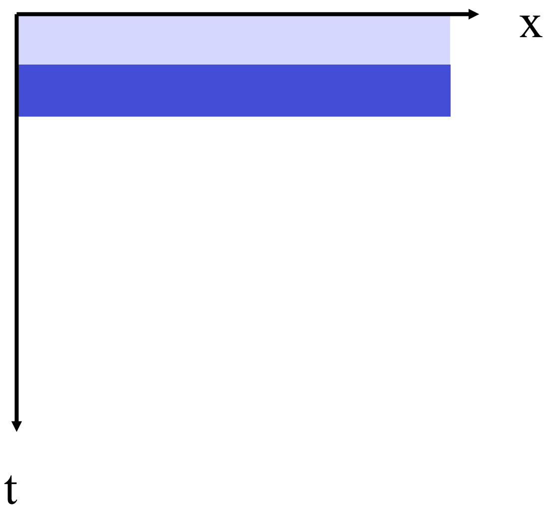

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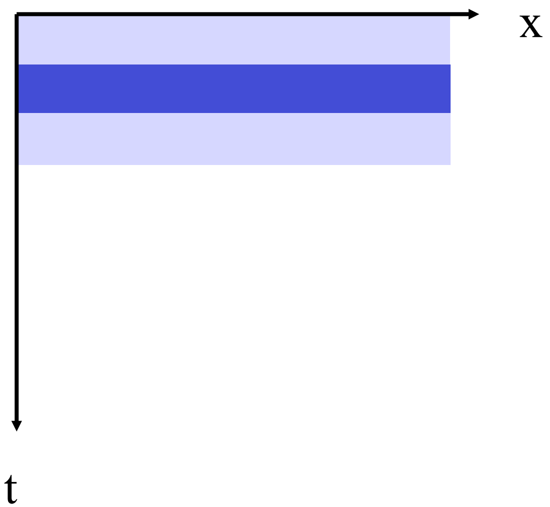

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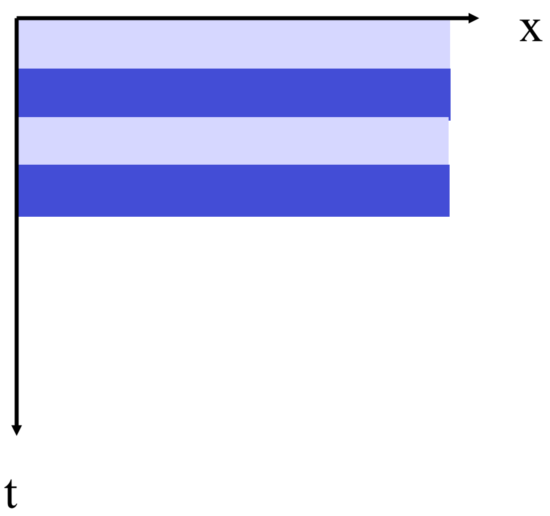

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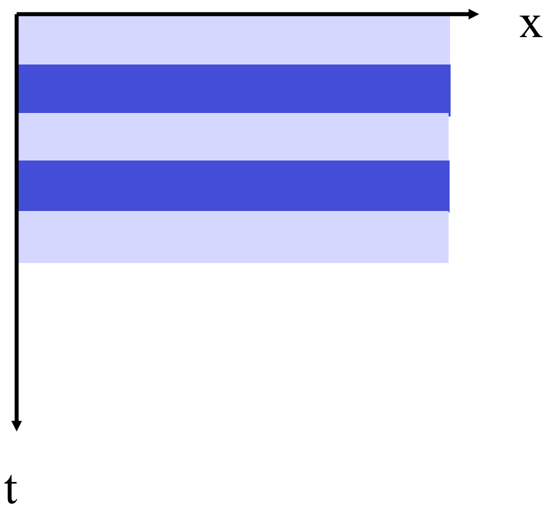

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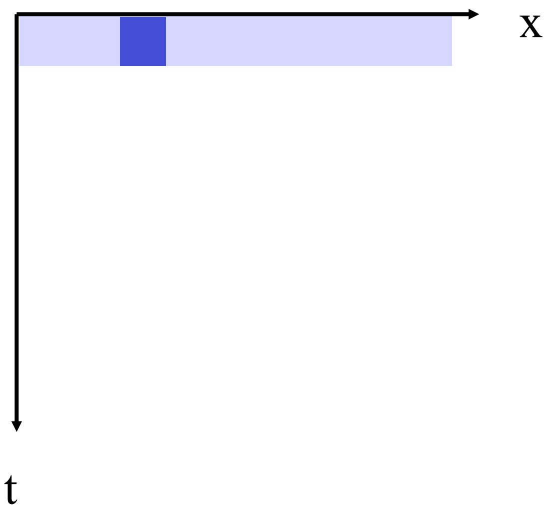

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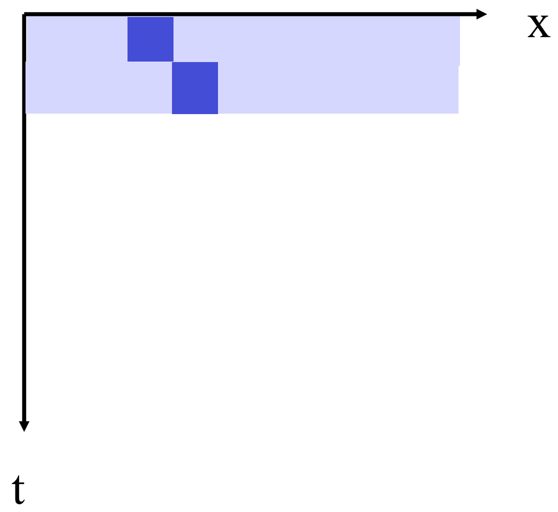

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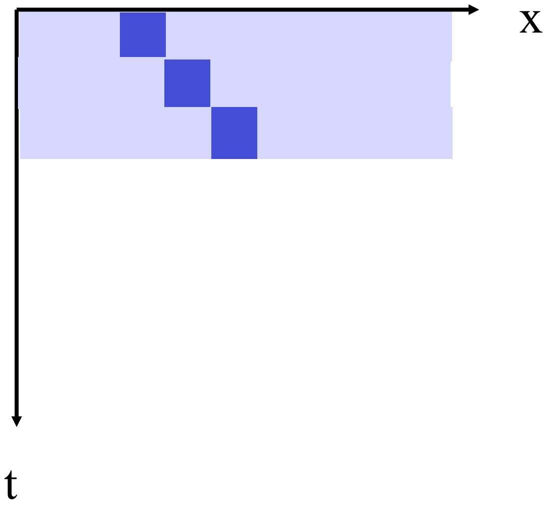

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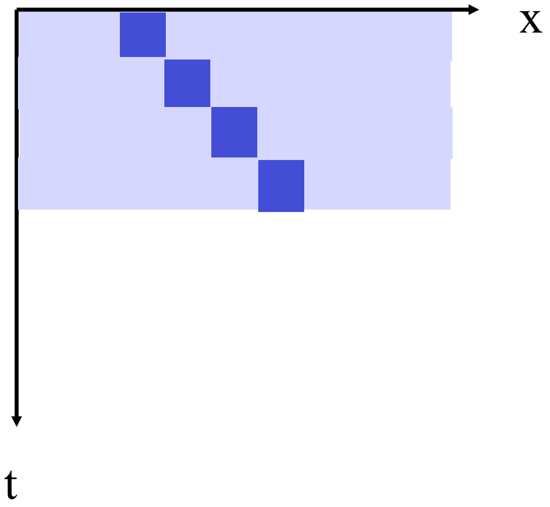

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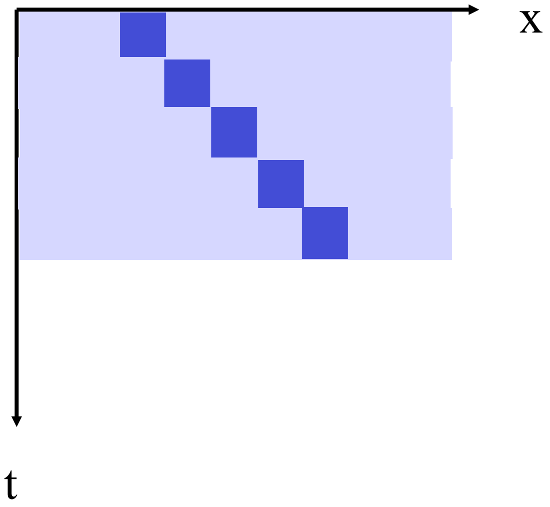

A representation for spatiotemporal patterns: Primitive patterns

- Consider a spatiotemporal slice
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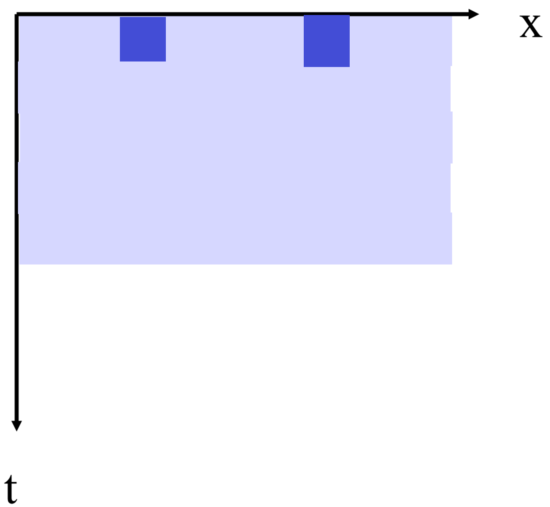

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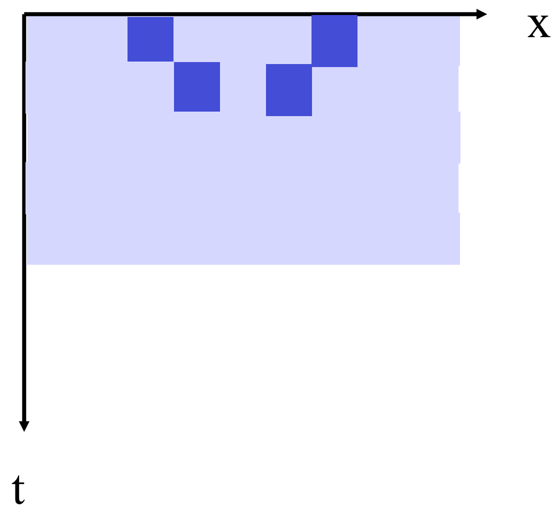

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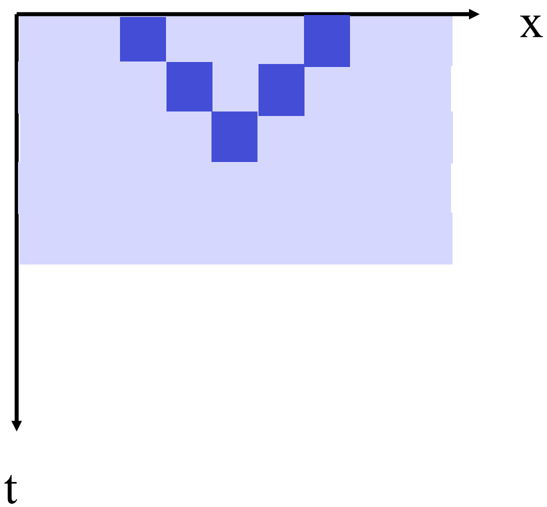

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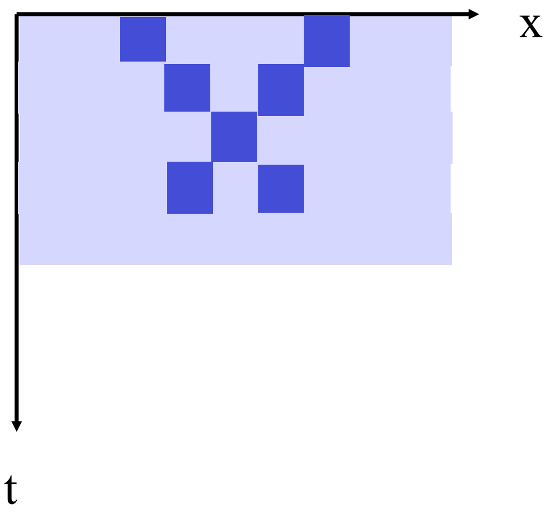

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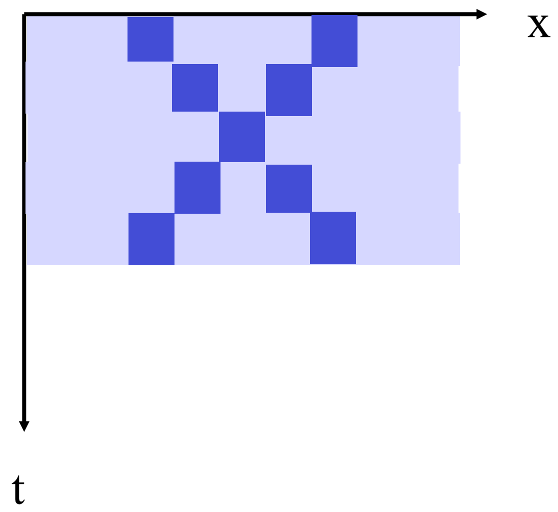

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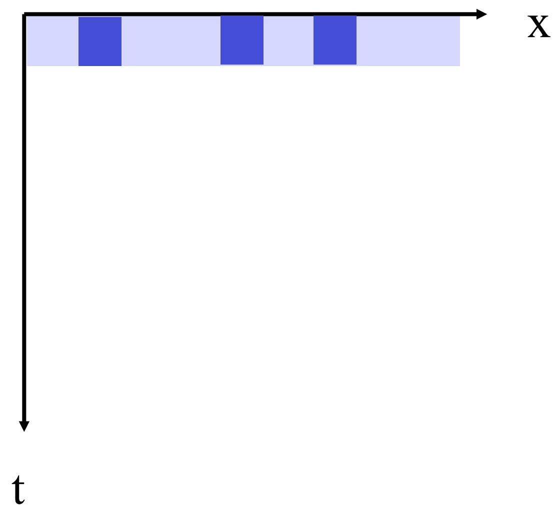
  - As an observer views a pattern, "randomly" structured in space and time.



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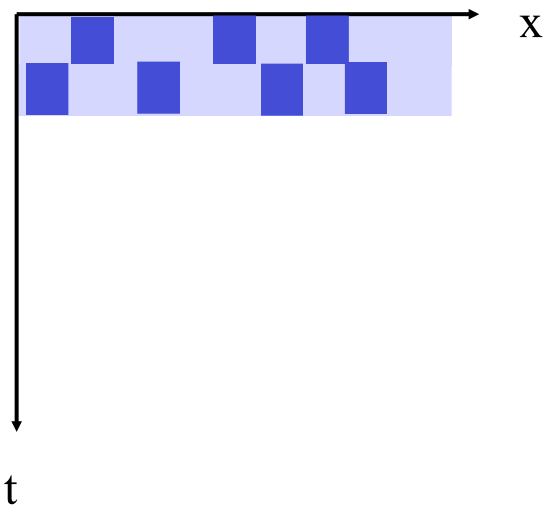

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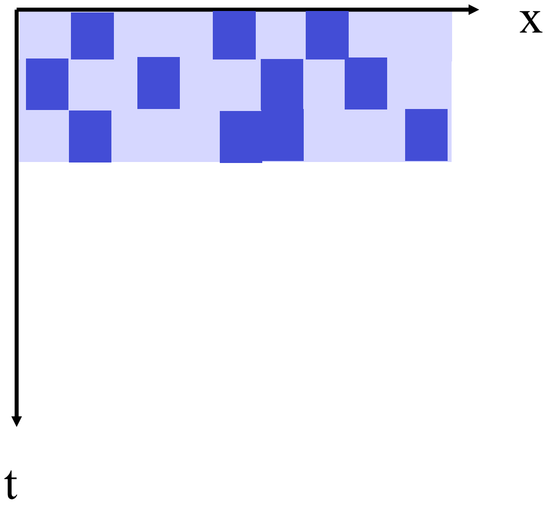

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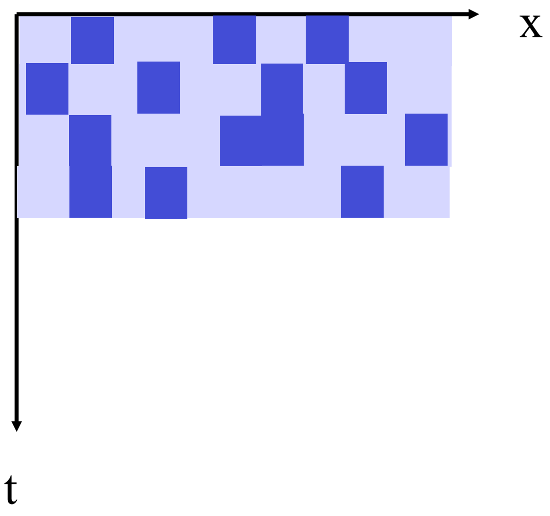

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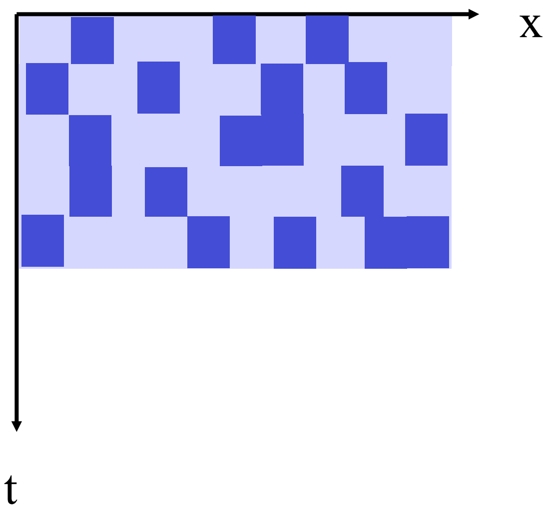
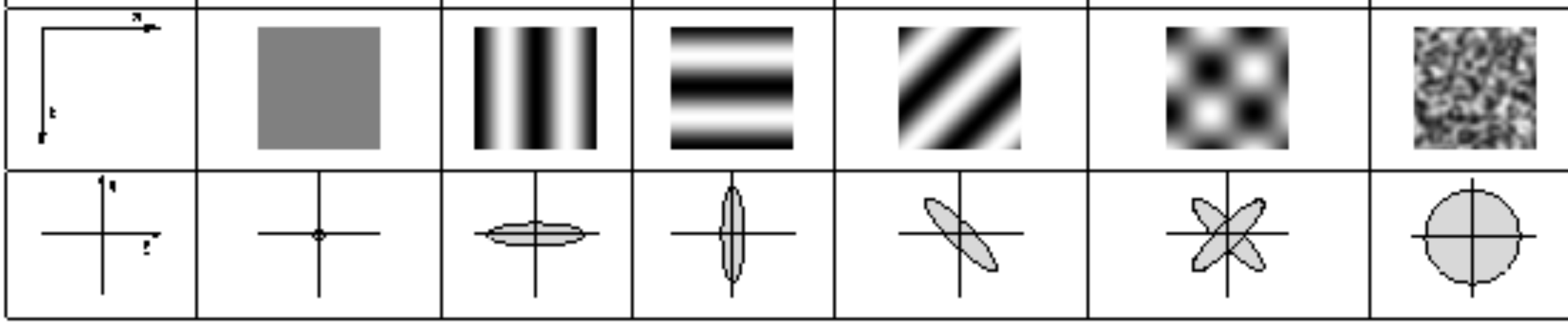


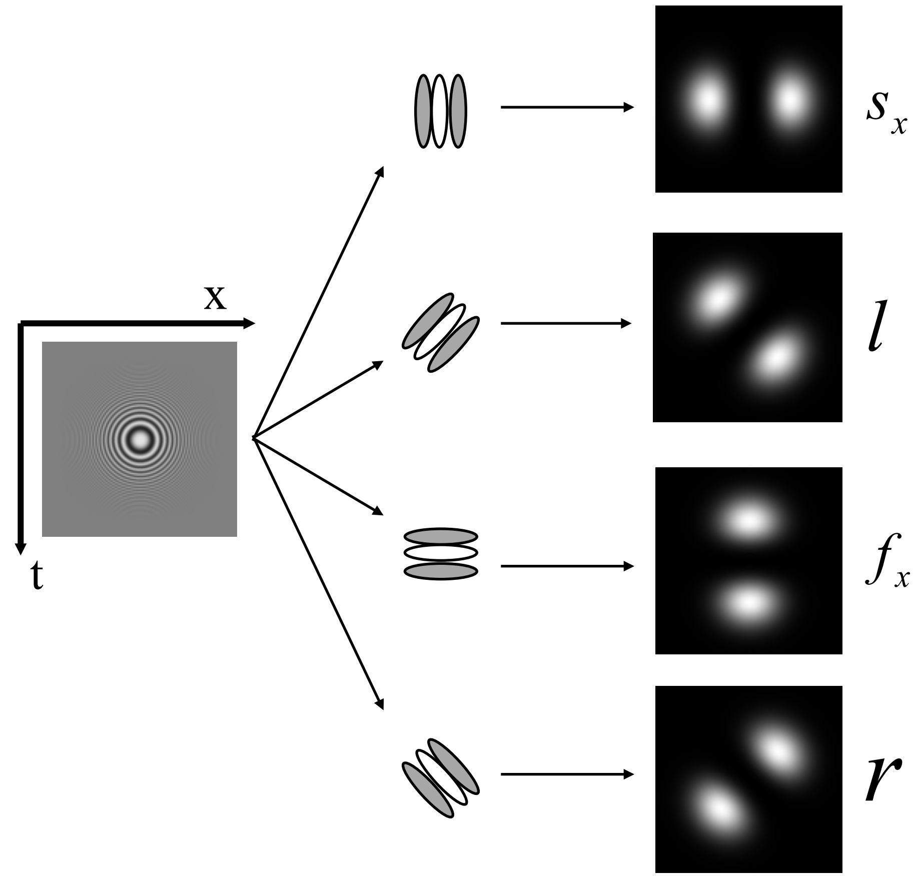
A representation for spatiotemporal patterns: Primitives

	Unstruc-tured	Static	Flicker	Coherent Motion	Incoherent Motion	Scintil-lation



Orientation in visual space-time: Filtering

- Apply filters tuned to 4 different orientations in both x-t and y-t domains.
- In general, might consider additional directions.
- Filter specifics:
  - Oriented bandpass filters in spatiotemporal slice.
  - Lowpass filter in orthogonal spatial dimension.
  - Pointwise squared to yield local "oriented energy".



Orientation in visual space-time: Normalization

- For any given orientation, the filter response is a joint function of
  - orientation
  - contrast

- Normalization yields purer measure of orientation

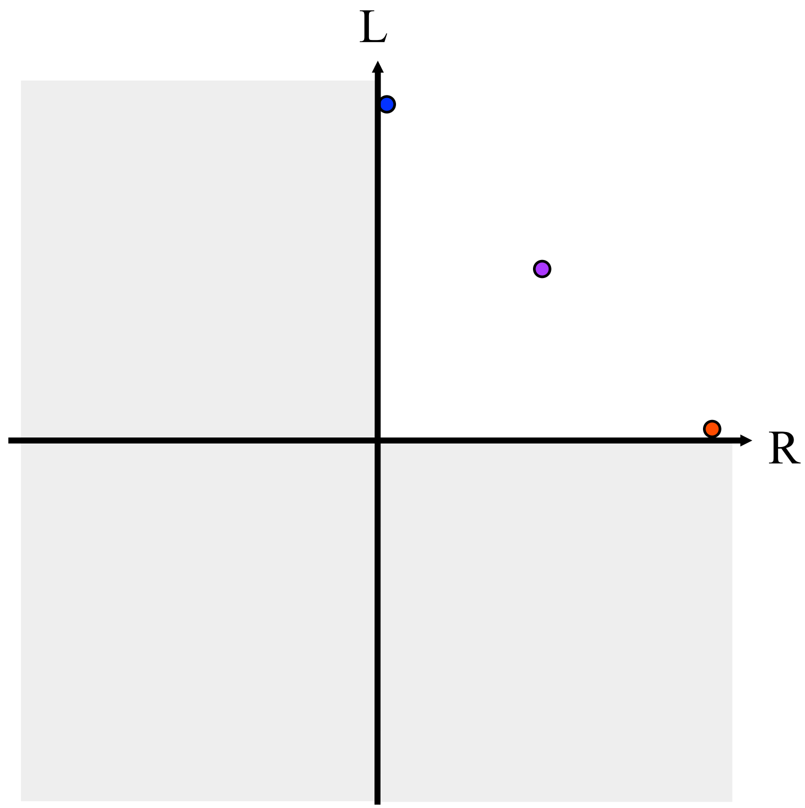
$$R(x,y,t) = \frac{r(x,y,t)}{r(x,y,t) + l(x,y,t) + s_x(x,y,t) + f_x(x,y,t) + \varepsilon}$$

with ვ a small bias added for stability.

- Similarly for l, s_x, f_x and their y-t counterparts.

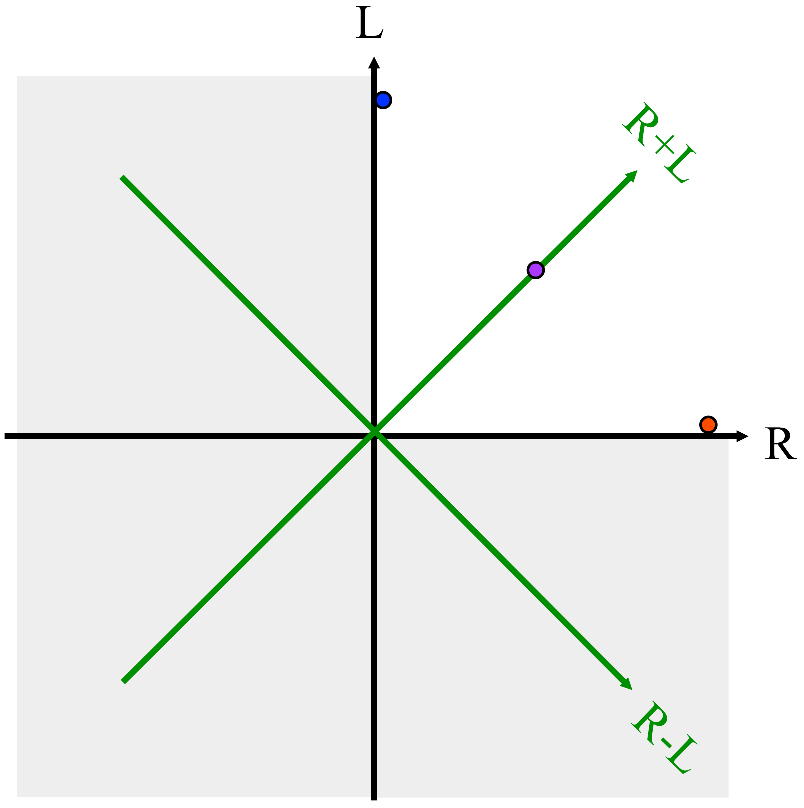
A representation for spatiotemporal patterns: Opponency and summation

- The R and L (U and D) components are ambiguous WRT coherent and incoherent motion.



A representation for spatiotemporal patterns: Opponency and summation

- The R and L (U and D) components are ambiguous WRT coherent and incoherent motion.
- Solution: Combine via
  - opponency R-L (U-D)
  - summation R+L (U+D)
- Geometrically a rotation of coordinate axes.

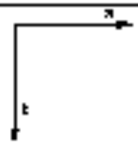
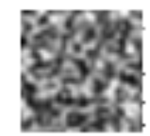
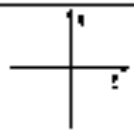
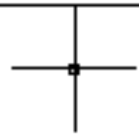
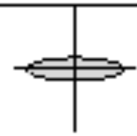
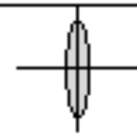
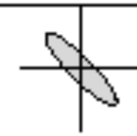
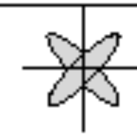
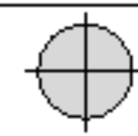


A representation for spatiotemporal patterns: Spatiotemporal representation

- Proposal: A four band representation for both the x-t and y-t dimensions.

x-t	y-t
$\|R - L\|$	$\|U - D\|$
$R + L$	$U + D$
S_x	S_y
F_x	F_y

A representation for spatiotemporal patterns:
Primitives projected on representation

	Unstruc-tured	Static	Flicker	Coherent Motion	Incoherent Motion	Scintil-lation
						
						
$\|R-L\|$	0	0	0	++	0	0
$R+L$	0	++	++	++	++++	++
S_x	0	++	0	+	+	+
F_x	0	0	++	+	+	+

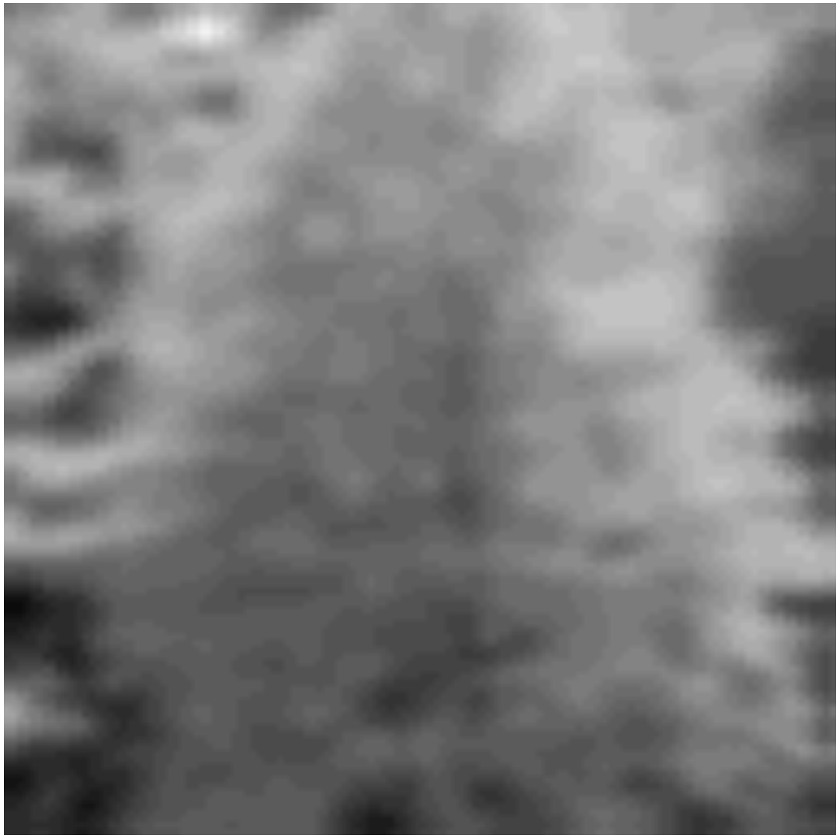
A representation for spatiotemporal patterns: Examples I

- A natural image sequence of each proposed class was acquired, (x,y,t) = (64,64,40).
  - Unstructured: featureless sky
  - static: motionless tree
  - flicker: smooth surface illuminated by lightning flashes
  - coherent motion: field of flowers under camera motion
  - incoherent motion: overlapped legs in complex motion
  - scintillation: rain striking a puddle

- Each sequence brought under proposed representation.

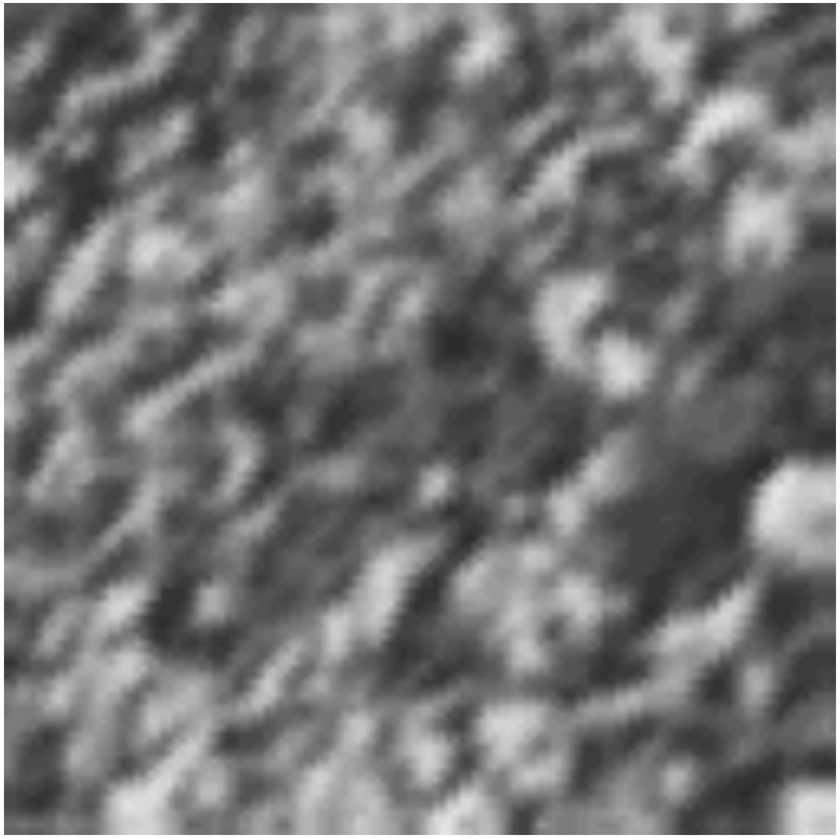
Unstructured

Static



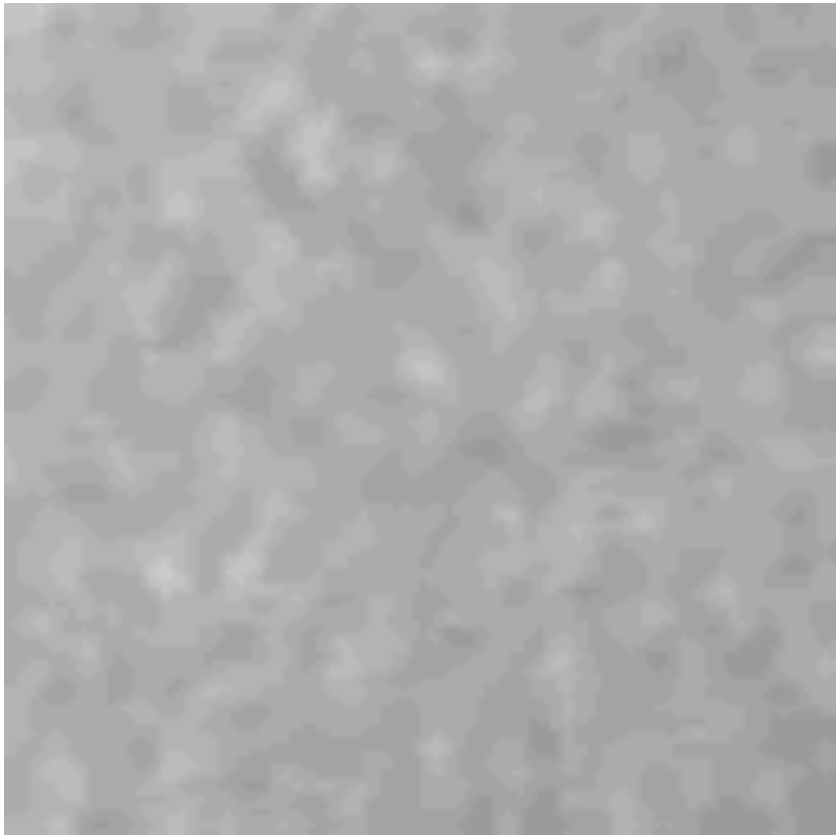
Flicker

Coherent motion

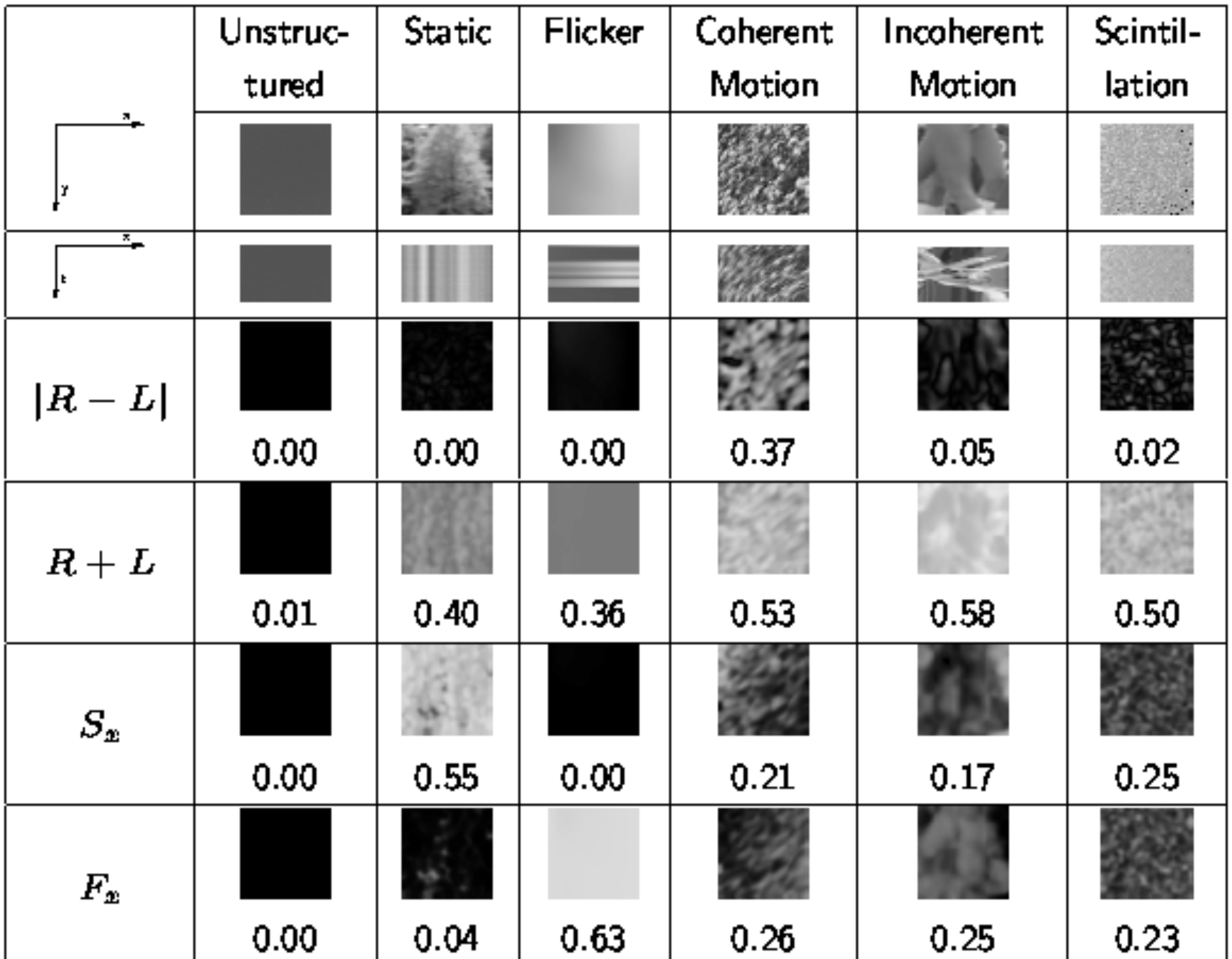


Incoherent motion

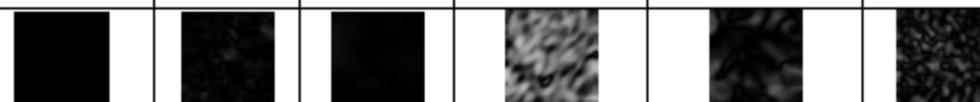
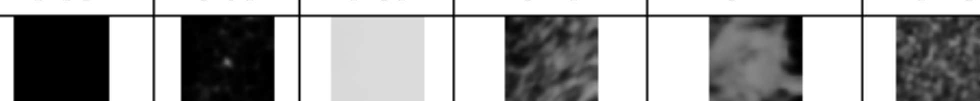
Scintillation



A representation for spatiotemporal patterns: Results x-t



A representation for spatiotemporal patterns: Results y-t

	Unstruc-tured	Static	Flicker	Coherent Motion	Incoherent Motion	Scintil-lation
						
						
$\lvert U - D \rvert$ 	0.00	0.00	0.00	0.34	0.02	0.02
$U + D$ 	0.01	0.38	0.36	0.52	0.45	0.50
S_y 	0.00	0.59	0.00	0.19	0.24	0.28
F_y 	0.00	0.03	0.64	0.29	0.29	0.21

A representation for spatiotemporal patterns: Remarks

- Have described a representation for distinguishing primitive spatiotemporal patterns.
- The representation makes use of oriented bandpass image decomposition.
- Initial empirical results support the hypothesis that the proposed representation can afford the desired distinctions.

Outline

- Introduction
- Orientation in visual space-time
- A representation for spatiotemporal patterns
- **Spatiotemporal boundaries**
- A framework for spatiotemporal analysis
- Applications
- Summary

Boundaries: Motivation

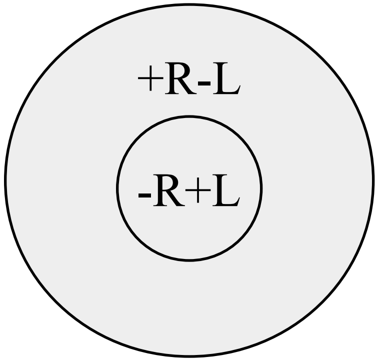
- Detection and localization of spatiotemporal boundaries is an important aspect of chunking information into meaningful pieces.

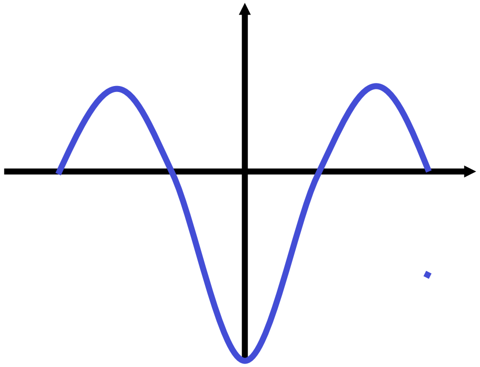
- Complimentary to the area-based analysis considered so far.

- Differential operators matched to the juxtaposition of contrasting spatiotemporal structure can be assembled from the primitive filter responses, S, F, R-L, R+L, etc.

Boundaries: Coherent motion

- Boundaries in coherent motion discriminate foreground/background.
- Coherent motion related to opponent bands R-L and U-D.
- Combine a spatial Laplacian with opponent filtering to yield double opponent operators.





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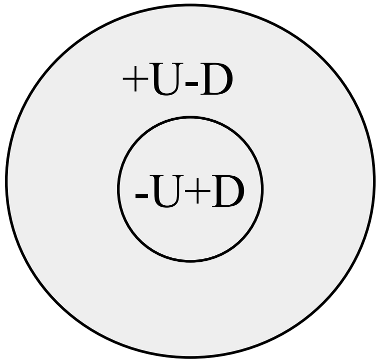
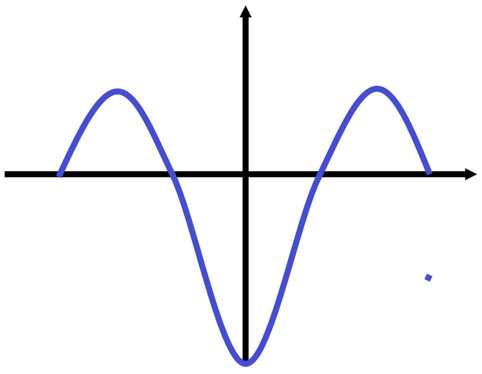
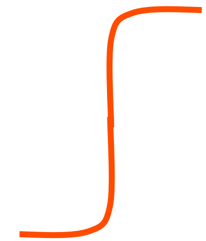




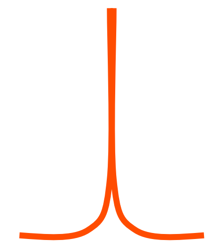
Boundaries: Signature

- Zero-crossings in the double-opponent motion operator output indicate coherent motion boundaries.
- Slope magnitude taken as strength of boundary signal.
- Sum signals from x-t and y-t dimensions.

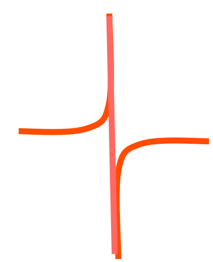
$R - L$



$D_x(R - L)$



$D_{xx}(R - L)$

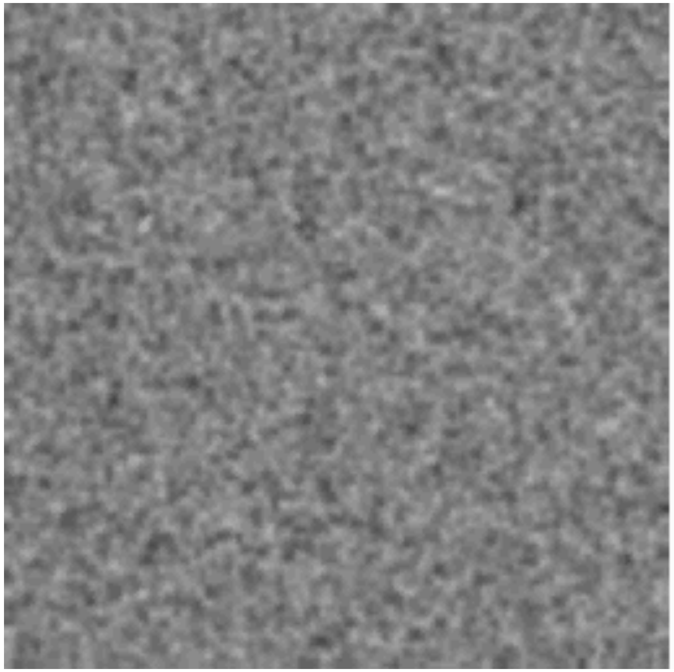


Boundaries: Examples II

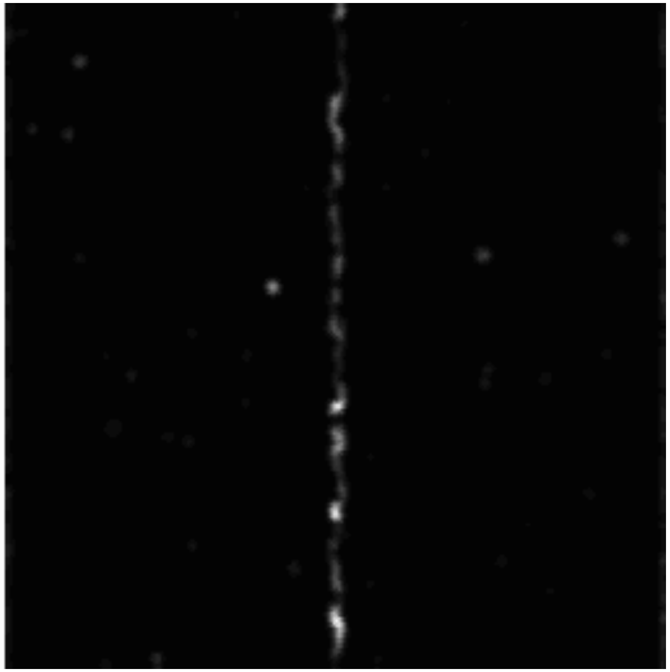
- Two image sequences depicting boundaries of coherent motion, (x,y,t) = (256,256,16).
  - random dot cinematogram: left and right sides of display in opposite horizontal motion.
  - natural image sequence: aerial view of tree canopy with movement relative to undergrowth due to camera motion; homogeneous texture of vegetation obscures boundary in any one image.

- Each sequence processed by proposed method for indicating coherent motion boundaries.

Boundaries: Results

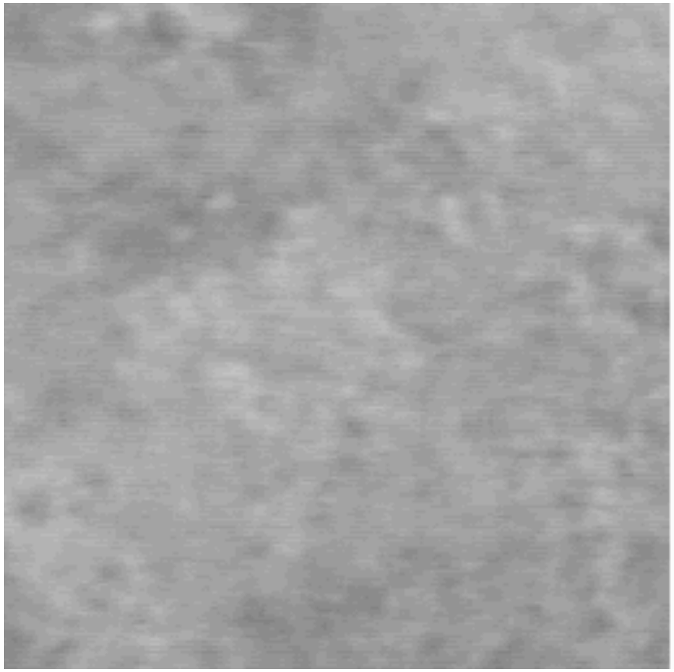


Frame of input sequence.



Motion boundary signal intensity.

Boundaries: Results



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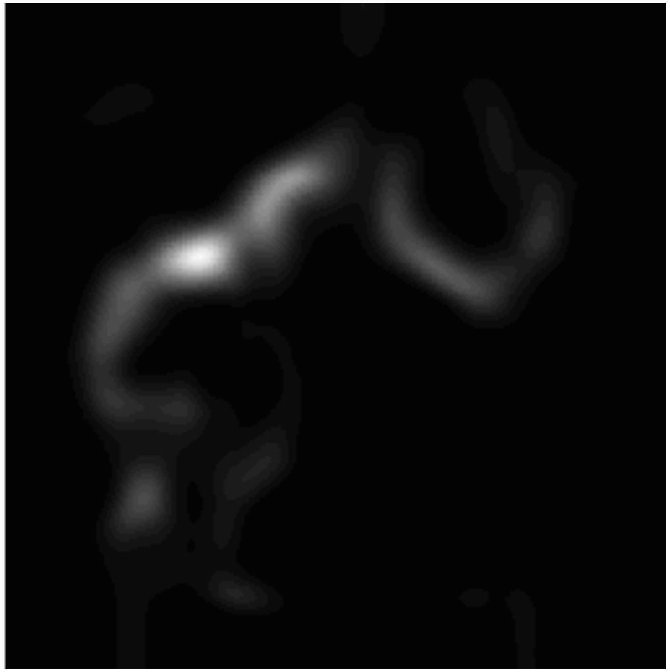

Motion boundary signal intensity.

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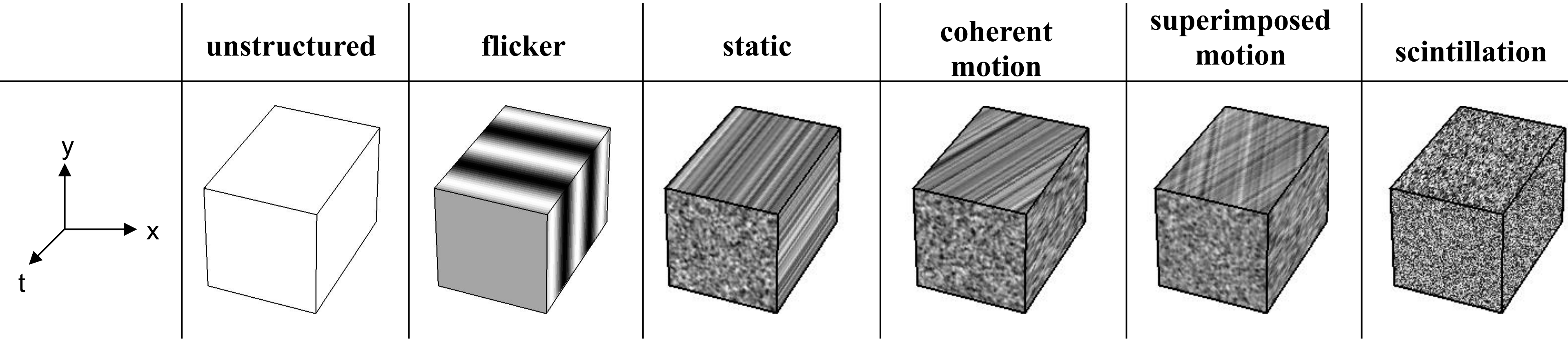
Framework: Local orientation



Appeal to orientation is not arbitrary

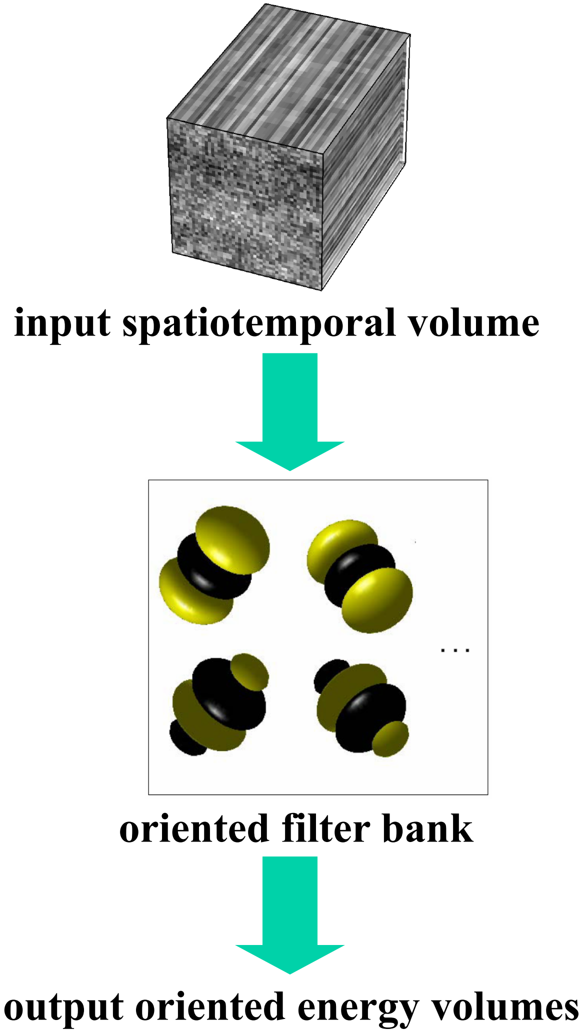
- The local orientation (or lack thereof) of a pattern is one of its most salient characteristics.
- Geometrically, orientation captures the local first-order correlation structure of a pattern, alternatively the local tangent.
- Provides a formal prerequisite to analysis of higher-contact constructions (e.g., curvature)
- For vision, local spatiotemporal orientation can have additional interpretations.
  - Image velocity is manifest as spatiotemporal orientation.
  - And more...

Framework: Filtering

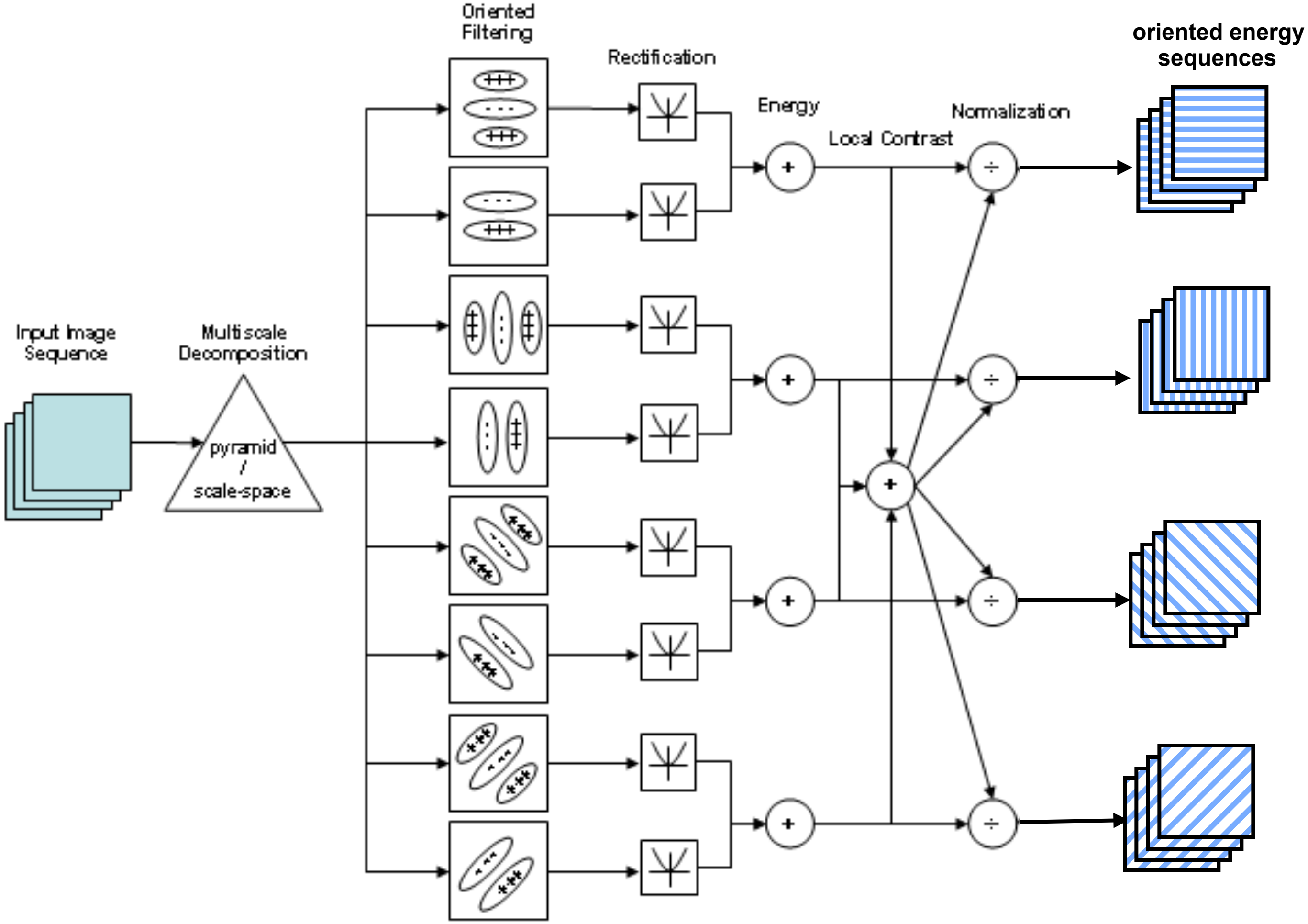
Orientation selectivity

- Goal is to analyze spatiotemporal data, $I(x, y, t)$, according to its local orientation structure.
- Choose a representation with multiple bands each tuned for certain orientations, θ, and scales in 3D (x, y, t).
- Filter specifics:
  - 3D Gaussian second derivatives, $G_{2\theta}$.
  - Corresponding Hilbert transforms, $H_{2\theta}$.
  - Rectified and summed in quadrature pairs to yield local "oriented energy".

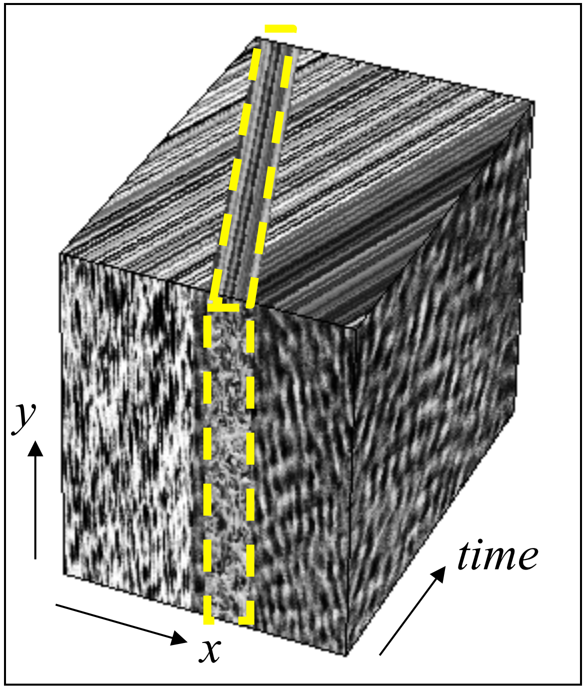
$$E_\theta(x,y,t) = \left[G_{2\theta} * I(x,y,t)\right]^2 + \left[H_{2\theta} * I(x,y,t)\right]^2$$



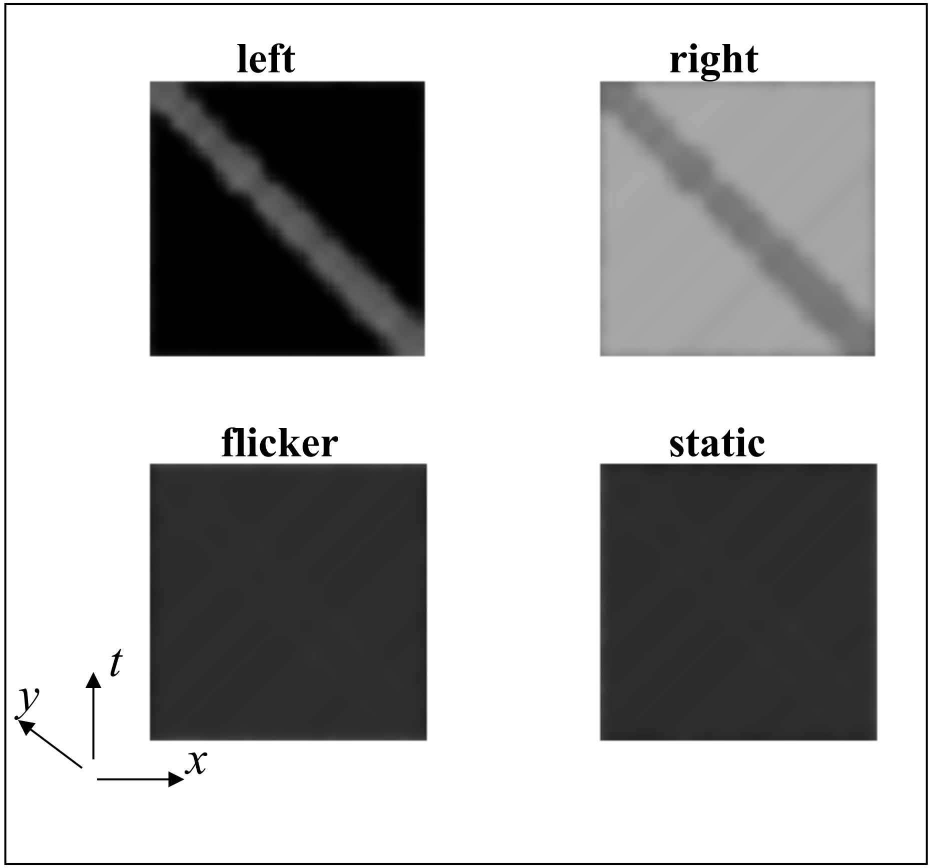
Framework: Architecture



Framework: Example



spatiotemporal volume

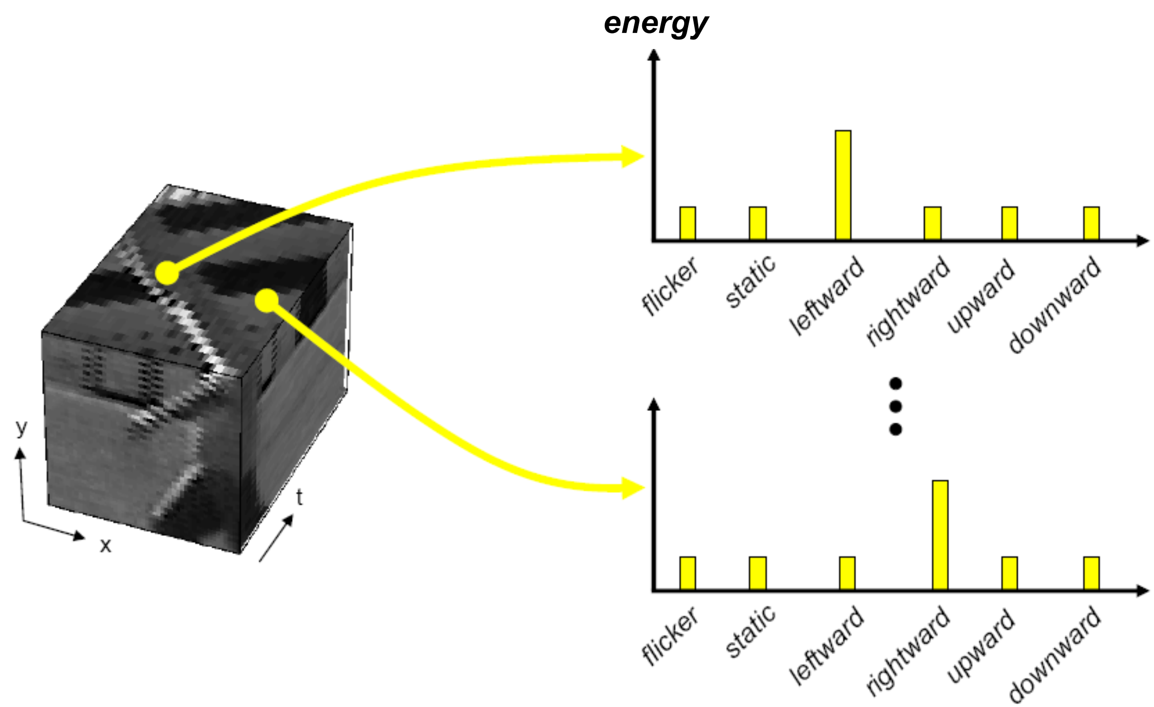


oriented energy volume

Framework: Distributions of oriented energy

Key ideas

- Build a distributed representation (i.e., histogram) at each point that measures the amount of energy for various kinds of spacetime oriented structures.
- Base subsequent analysis on the distribution of oriented energies across space and time.



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Applications

Examples provided in lecture.

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