Sampling and Reconstruction of Visual Appearance

CSE 274 [Winter 2018], Lecture 7

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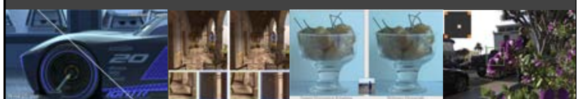
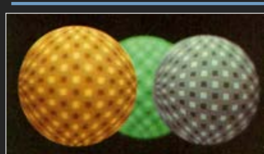


Basics of Denoising, Frequency Analysis

Monte Carlo Rendering (biggest application)

- Basic idea of denoising
- Frequency analysis one key concept
- Presentation of key papers at next class
- Relevant to other applications as well

Cook et al. [1984] results



depth of field

motion blur

soft shadows

glossy reflection

Motivation

- Distribution effects (depth of field, motion blur, global illumination, soft shadows) are slow. Many dimensions sample

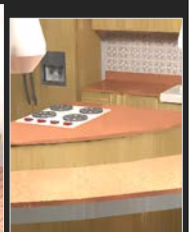
- Ray Tracing physically accurate but slow, not real-time
- Can we adaptively sample and filter for fast, real-time?

Sample result

Path traced scene / Filtered scene

[Kalantari et al. 2015]

scene by Jo Ann Elliott



4 samples/pixel (40.8 sec)

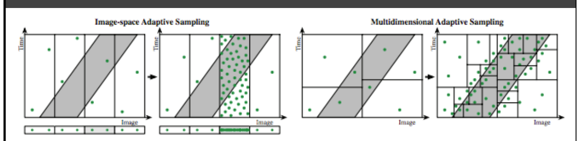
using only post-process filter!

Adaptive sampling + reconstruction

- These algorithms use 2 kinds of noise reduction strategies, sometimes combined:
  1. Adaptive sampling algorithms
     - Use information from renderer to position new samples better to reduce noise
  2. Reconstruction (filtering) algorithms
     - Use information from renderer to remove MC noise directly
- Both methods have been explored in the past, but new algorithms make remarkable advances

Multi-Dimensional Adaptive Sampling

- Hachisuka, Jarosz, … Zwicker, Jensen [MDAS 2008]
- Scenes with motion blur, depth of field, soft shadows
- Involves high-dimensional integral, converges slowly
- Exploit high-dimensional info to sample adaptively
- Sampling in 2D image plane or other dims inadequate
  - Need to consider full joint high-dimensional space

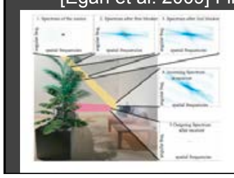


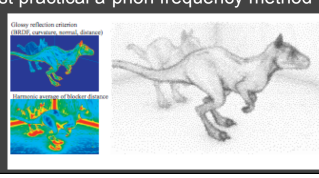
Multi-Dimensional Adaptive Sampling

Motion Blur and Depth of Field 32 samples per pixel

Resurgence (2008 -)

- Eurographics 2015 STAR report by Zwicker et al.
  - Papers below are key a-priori, frequency analysis methods
  - Many other approaches to be discussed in class
- [Durand et al. 2005] *Frequency analysis light transport*
  - Key theoretical ideas, but not initially very practical
- [Chai et al. 2000] Plenoptic Sampling (wedge spectrum)
- [Egan et al. 2009] First practical a-priori frequency method





A Frequency Analysis of Light Transport

F. Durand, MIT CSAIL

N. Holzschuch, C. Soler, ARTIS/GRAVIR-IMAG INRIA

E. Chan, MIT CSAIL

F. Sillion, ARTIS/GRAVIR-IMAG INRIA

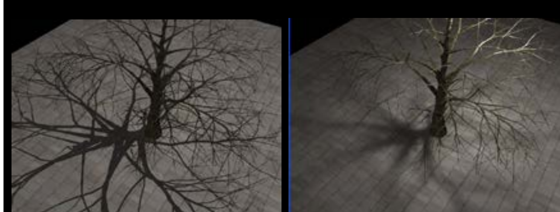
Illumination effects

- Blurry reflections:

From [Ramamoorthi and Hanrahan 2001]

Illumination effects

- Shadow boundaries:



Point light source | Area light source

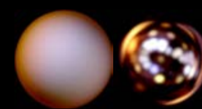
Problem statement

- How does light interaction in a scene explain the frequency content?
- Theoretical framework:
  - Understand the frequency spectrum of the radiance function
  - From the equations of light transport

Unified framework:

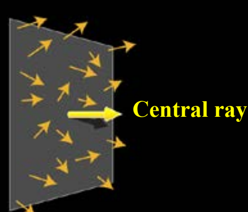
- Spatial frequency (e.g. shadows, textures)

- Angular frequency (e.g. blurry highlight)



Local light field

- 4D light field, around a *central ray*



Local light field

- 4D light field, around a *central ray*
- We study its spectrum during transport

Local light field

- 4D light field, around a *central ray*
- We study its spectrum during transport

Local light field

- 4D light field, around a *central ray*
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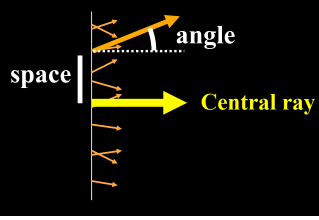
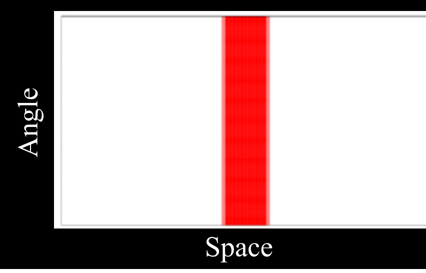
Local light field parameterization

- Space and angle



Local light field representation

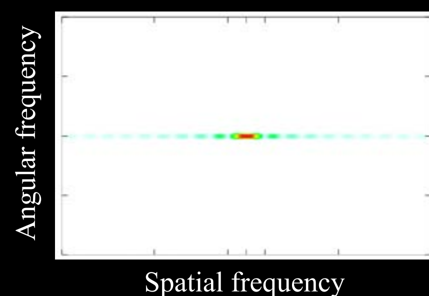
- Density plot:



Local light field Fourier spectrum

- We are interested in the Fourier spectrum of the local light field
- Also represented as a density plot

Local light field Fourier spectrum

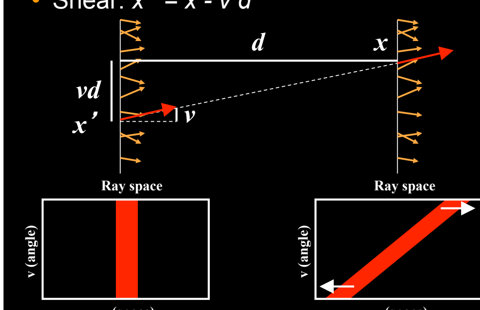


Fourier analysis 101

- Spectrum corresponds to blurriness:
  - Sharpest feature has size ~ $1/F_{max}$
- Convolution theorem:
  - Multiplication of functions: spectrum is convolved
  - Convolution of functions: spectrum is multiplied
- Classical spectra:
  - Box becomes sinc
  - Dirac becomes constant

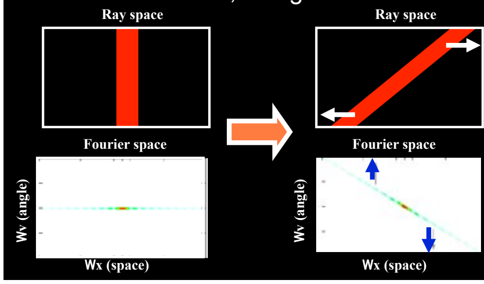
Transport

- Shear: $x' = x - v\,d$



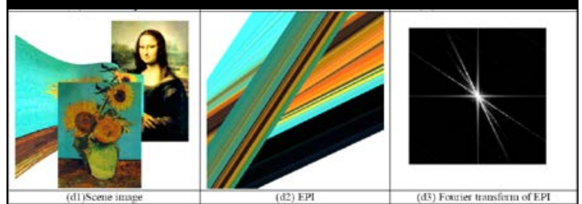
Transport in Fourier space

- Shear in primal: $x' = x - v\,d$
- Shear in Fourier, along the other dimension



Transport becomes Shear

- This is consistent with light field spectra
  [Chai et al. 00, Isaksen et al. 00]



From [Chai et al. 2000]

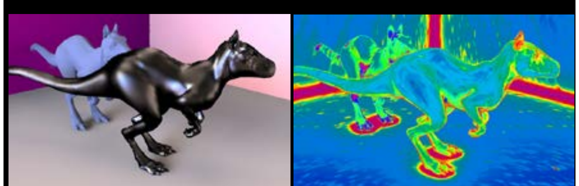
BRDF integration

- Ray-space: ***convolution***
  - Outgoing light:
    convolution of incoming light and BRDF
  - For rotationally-invariant BRDFs

- Fourier domain: ***multiplication***
  - Outgoing spectrum: multiplication of incoming spectrum and BRDF spectrum

Adaptive shading sampling

- Per-pixel prediction of max. frequency (bandwidth)
  - Based on curvature, BRDF, distance to occluder, etc.
  - No spectrum computed, just estimate max frequency



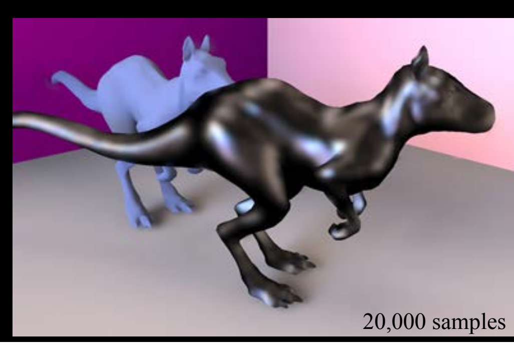
Per-pixel bandwidth criterion

Adaptive shading sampling

- Per-pixel prediction of max. frequency (bandwidth)
  - Based on curvature, BRDF, distance to occluder, etc.
  - No spectrum computed, just estimate max frequency

Shading samples

Uniform sampling

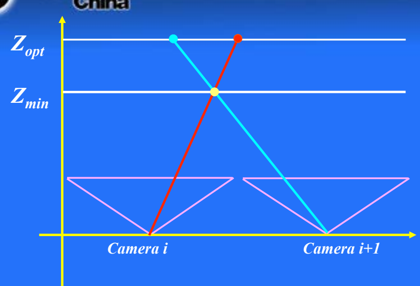


Adaptive sampling

Plenoptic Sampling

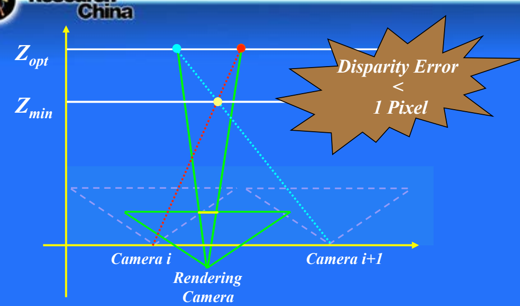
- Plenoptic Sampling. *Chai, Tong, Chan, Shum 00*
- Signal-processing on light field
- Minimal sampling rate for antialiased rendering
- Relates to depth range, Fourier analysis
- Fourier spectra derived for 2D light fields for simplicity. Same ideas extend to 4D
- Key paper in many newer methods on sheared and axis-aligned filtering for adaptive sampling

A Geometrical Intuition



Siggraph'2000, July 27, 2000

A Geometrical Intuition

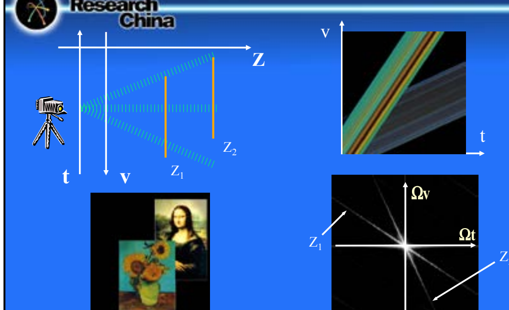


Siggraph'2000, July 27, 2000

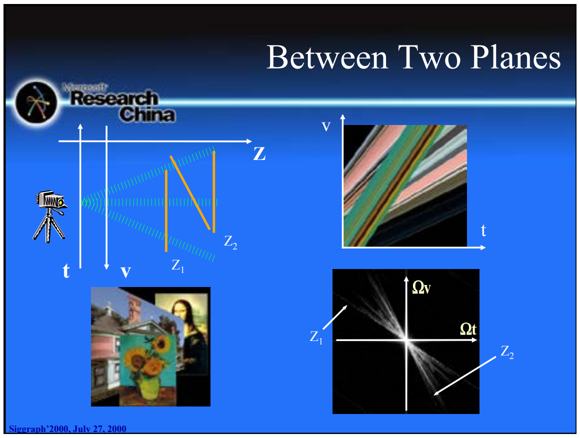
A Constant Plane

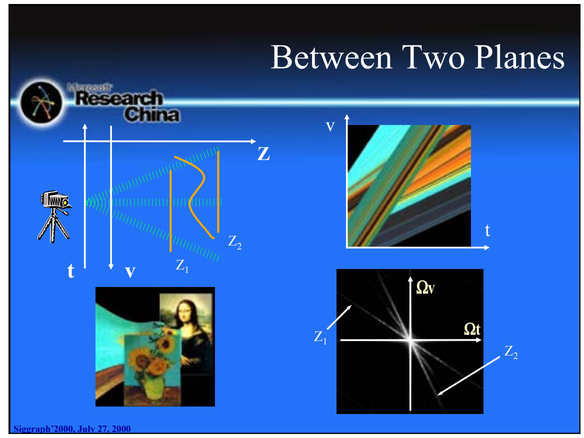
Siggraph'2000, July 27, 2000

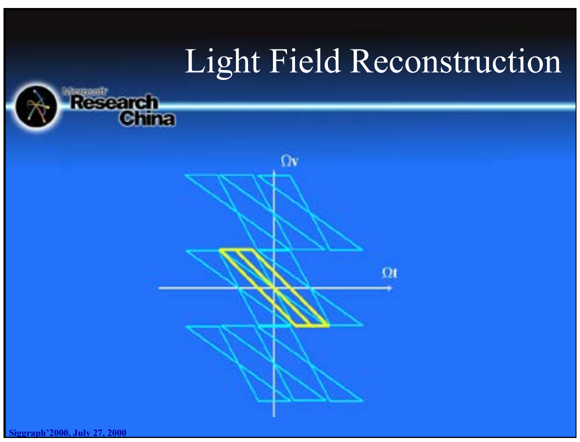
Two Constant Planes

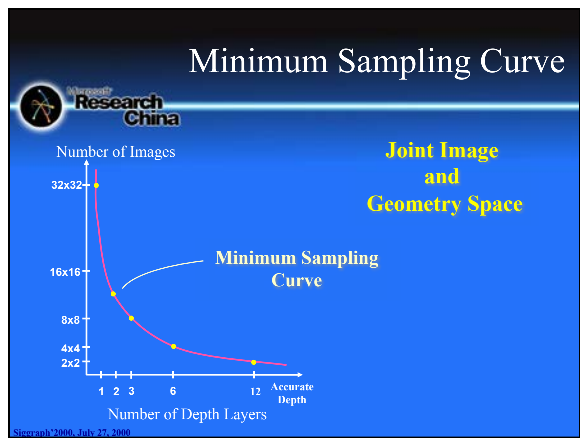


Siggraph'2000, July 27, 2000

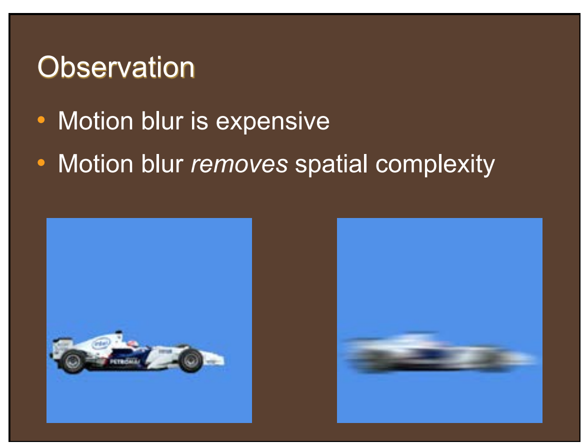

Between Two Planes
Research China
Z
v
t
v
Z1
Z2
t
Ωv
Ωt
Z1
Z2
Siggraph'2000, July 27, 2000

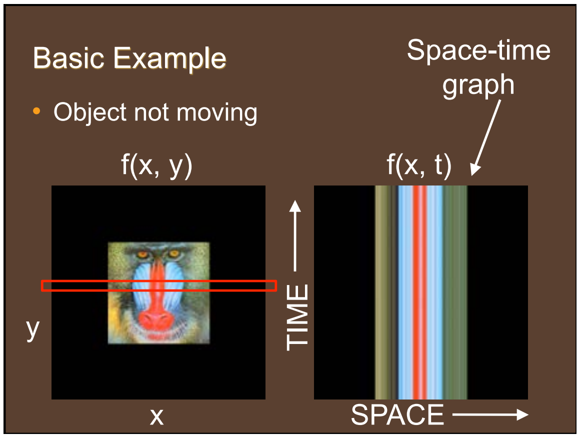

Between Two Planes
Research China
Z
v
t
v
Z1
Z2
t
Ωv
Ωt
Z1
Z2
Siggraph'2000, July 27, 2000

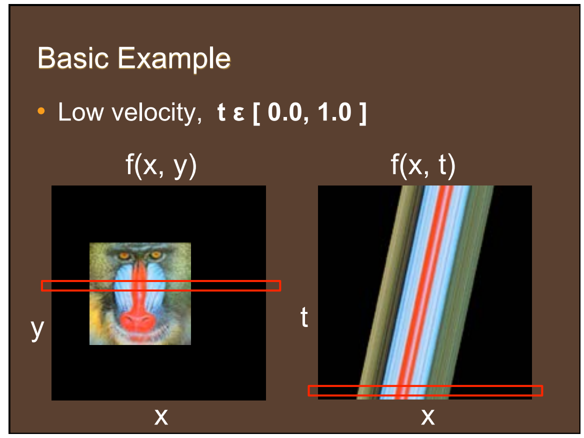

Light Field Reconstruction
Research China
Ωv
Ωt
Siggraph'2000, July 27, 2000

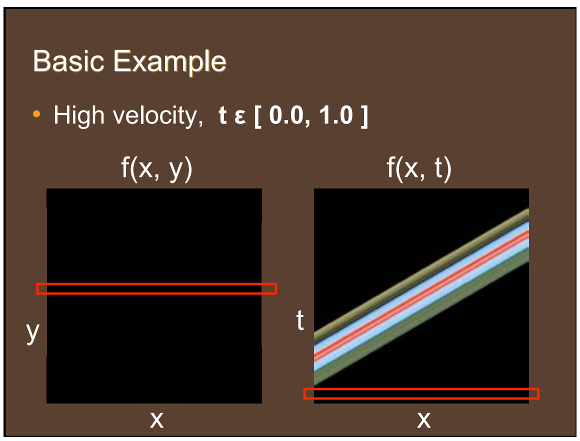

Minimum Sampling Curve
Research China
Number of Images
Joint Image
and
Geometry Space
32x32
16x16
8x8
4x4
2x2
Minimum Sampling
Curve
1 2 3 6 12
Accurate
Depth
Number of Depth Layers
Siggraph'2000, July 27, 2000

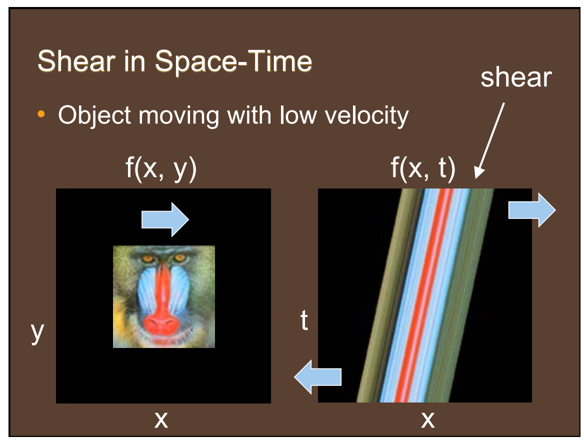

Frequency Analysis and
Sheared Reconstruction for
Rendering Motion Blur
Kevin Egan Columbia University
Yu-Ting Tseng Columbia University
Nicolas Holzschuch INRIA -- LJK
Frédo Durand MIT CSAIL
Ravi Ramamoorthi University of California, Berkeley
SIGGRAPH2009 NEW ORLEANS

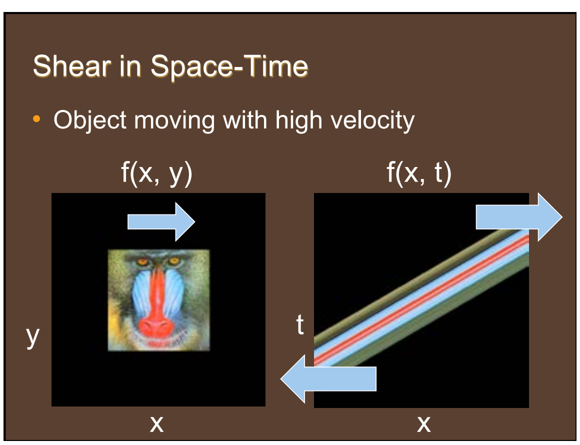

Observation
• Motion blur is expensive
• Motion blur removes spatial complexity

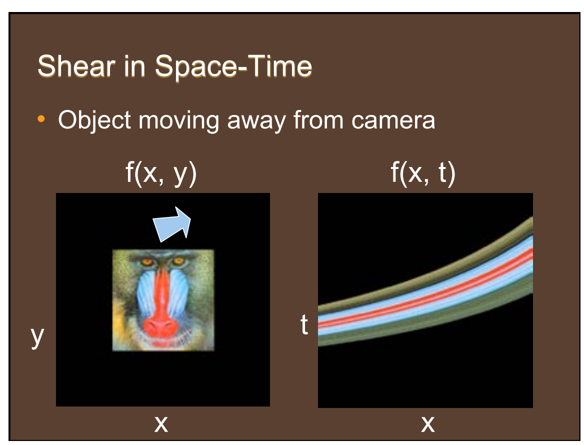

Basic Example
• Object not moving
Space-time graph
f(x, y)
f(x, t)
y
x
TIME
SPACE


Basic Example
• Low velocity, t ε [0.0, 1.0]
f(x, y)
f(x, t)
y
x
t
x


Basic Example
• High velocity, t ε [0.0, 1.0]
f(x, y)
f(x, t)
y
x
t
x

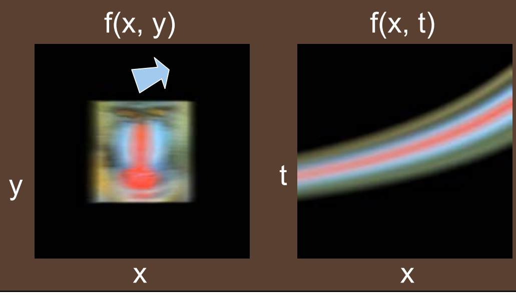

Shear in Space-Time
• Object moving with low velocity
shear
f(x, y)
f(x, t)
y
x
t
x


Shear in Space-Time
• Object moving with high velocity
f(x, y)
f(x, t)
y
x
t
x


Shear in Space-Time
• Object moving away from camera
f(x, y)
f(x, t)
y
x
t
x

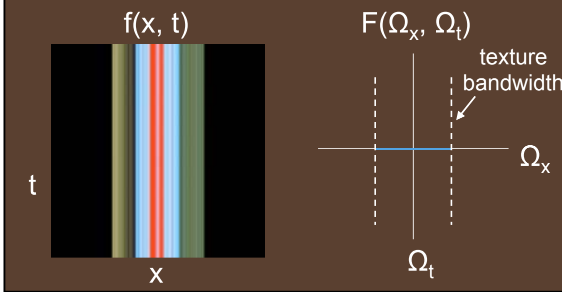
Basic Example

- Applying shutter blurs across time



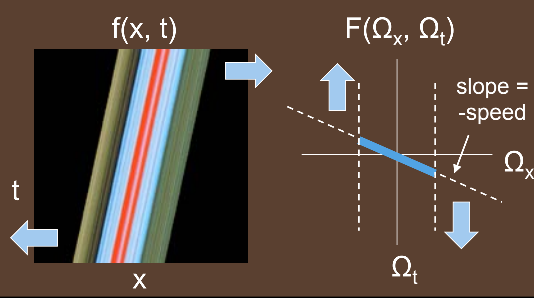
Basic Example – Fourier Domain

- Fourier spectrum, zero velocity



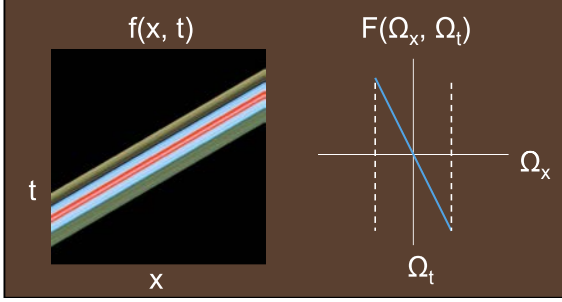
Basic Example – Fourier Domain

- Low velocity, small shear in both domains



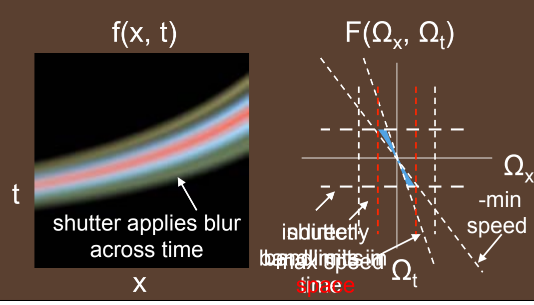
Basic Example – Fourier Domain

- Large shear



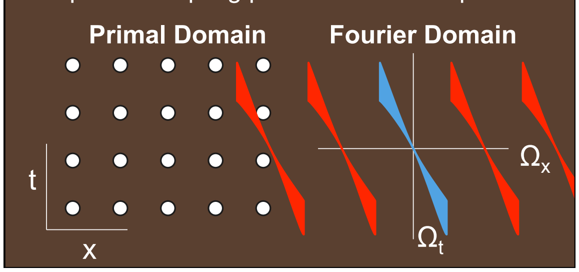
Basic Example – Fourier Domain

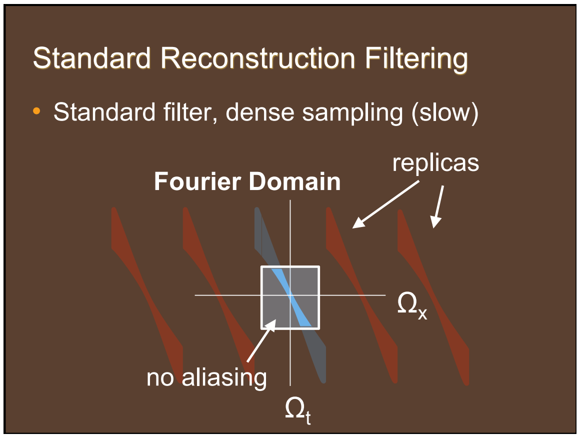
- Non-linear motion, wedge shaped spectra

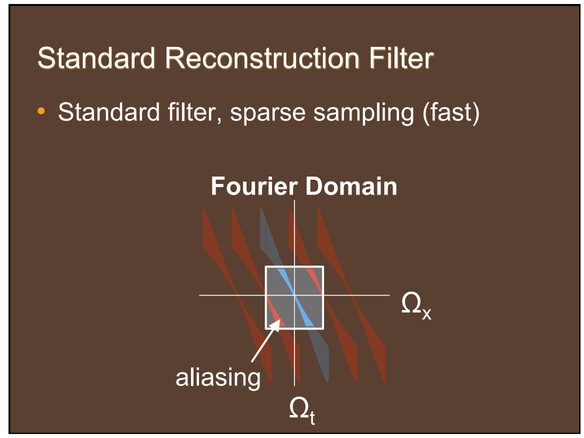


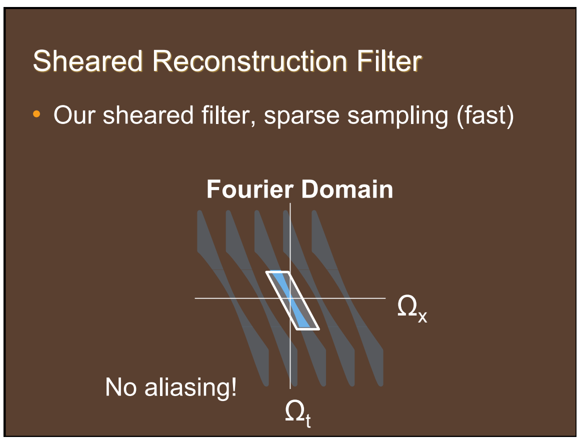
Sampling in Fourier Domain

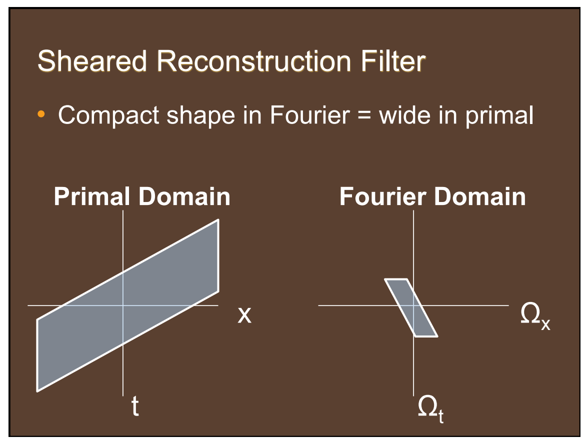
- Sampling produces replicas in Fourier domain
- Sparse sampling produces dense replicas

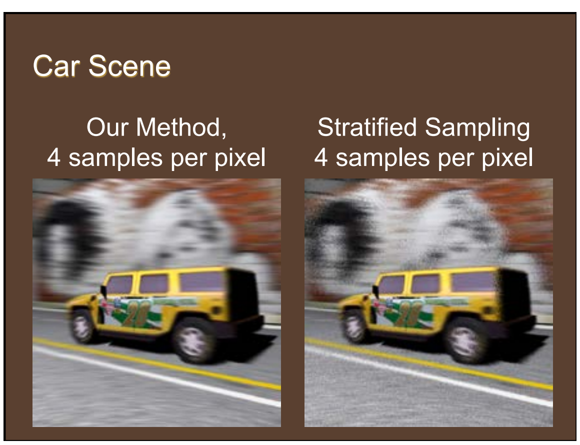


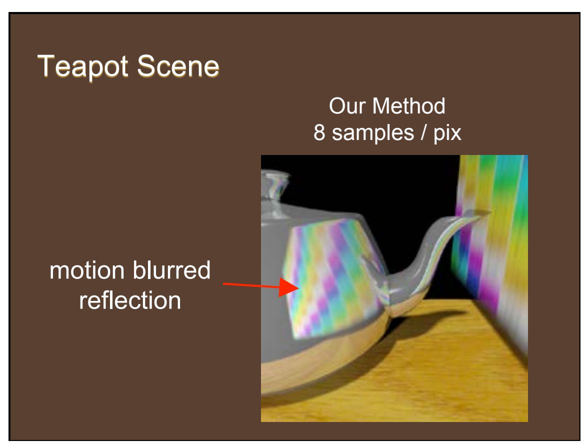

Standard Reconstruction Filtering
• Standard filter, dense sampling (slow)
Fourier Domain
replicas
Ω_x
no aliasing
Ω_t


Standard Reconstruction Filter
• Standard filter, sparse sampling (fast)
Fourier Domain
Ω_x
aliasing
Ω_t


Sheared Reconstruction Filter
• Our sheared filter, sparse sampling (fast)
Fourier Domain
Ω_x
No aliasing!
Ω_t


Sheared Reconstruction Filter
• Compact shape in Fourier = wide in primal
Primal Domain
Fourier Domain
x
t
Ω_x
Ω_t


Car Scene
Our Method,
4 samples per pixel
Stratified Sampling
4 samples per pixel


Teapot Scene
Our Method
8 samples / pix
motion blurred
reflection

Ballerina Video

Ballerina sequence
(8 samples/pixel)

Note smooth motion-blur
of dress and shadows

Frequency Analysis
and Sheared Reconstruction
for Rendering Motion Blur

ID: 0034