Computer Graphics - Week 8

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Questions about Last Week ?

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Comments about the Assignment

- **Deadline for 2nd assignment extended to Friday March 12 at 5:30 pm**
  - Regular rules for late submission apply
- **Post-mortem about 1st assignment**
  - We will subtract points for bad Readme files
  - Programs have to run !!
    At least tell us they don't work.
  - Programming should involve some upfront thinking
    - Drawing each planet separately is somewhat inelegant
    - Formatting and Comments !!!
  - Questions are encouraged ...
    but read the assignment and read our answers to your questions
  - If not explicitly stated otherwise, teamwork is **not** permitted

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Overview of Week 3

- **Aliasing and Anti-aliasing**
- **Summary of raster graphics pipeline**

- **VRML**

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Anti-aliasing

- Aliasing are artifacts introduced by sampling the object geometry, e.g. staircasing, broken up polygons, blinking objects in animations etc.
- First, a short overview of sampling theory to further the understanding of sampling artifacts
- Then, we will study different techniques to limit or eliminate aliasing effects: anti-aliasing
- Last, we will look at implementation techniques to implement anti-aliasing, e.g. using the alpha channel

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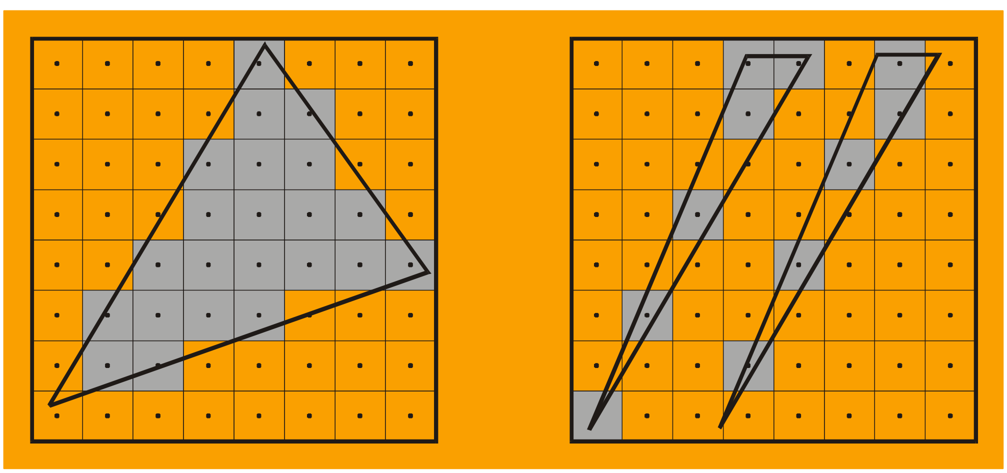
Aliasing: Examples

- Staircasing
- Broken-up objects
- Blinking (missed) objects



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Aliasing: Root Cause

- **Aliasing is caused by sampling objects with insuffcient sampling frequency**
  - Shannon's sampling theorem states that reconstruction of a sampled signal can only be accomplished if the signal is sampled with a frequency at least with twice the highest frequency component of the signal.
  - In practice, even higher sampling frequency is necessary.
- **Most objects in computer graphics contain infinite frequency components**
  - At the edges the signal changes instantaneously
  - Therefore, aliasing is a ubiquitous problem in graphics

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Anti-aliasing: Super-sampling

- **An obvious remedy to aliasing is to increase the sampling frequency**
  - This means to render images at a higher pixel resolution
  - Yet, super-sampling is still a point sampling process
- **Obviously, this will alleviate but not solve the problem**
  - Super-sampling misses fewer objects + creates smaller staircases
  - However it does not ensure proper sampling of all features

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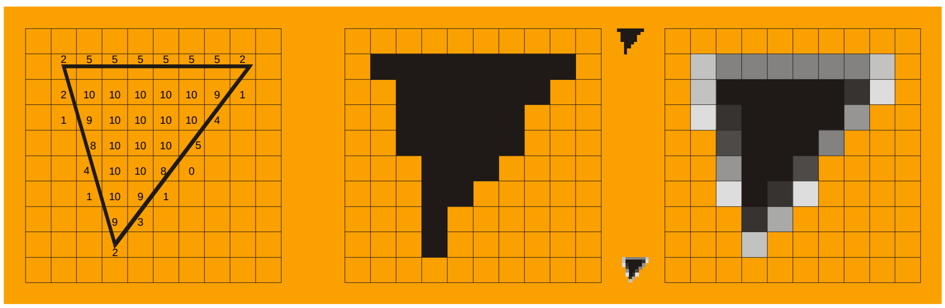
Anti-aliasing: Area Sampling (1)

- **Point sampling is a hit-or-miss proposition**

- **Instead of that binary decision, we prefer to have a sliding scale that indicates how much an object contributes to a pixel**
- **This approach is called area sampling**



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Anti-aliasing: Area Sampling (2)

- **Compute the contribution an object makes to a pixel**
  - Primitives are assumed to cover a finite area, even points and lines

- **Computation either analytical and by oversampling**
  - Analytical approaches
    - Compute the exact pixel area covered by a primitive for all pixels contributing to the anti-aliasing filter
    - Weight the area by that filter function
    - Write the pixel

  - Oversampling, approximates true area-sampling
    - Sample the image at a higher frequency
    - Compute a weighted average of all subpixels within the filter area
    - Write the pixel

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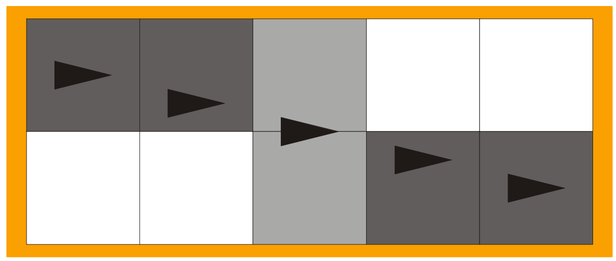
Anti-aliasing: Filtering (1)

- **Once the primitives contribution to the pixel has been determined, it must be translated into a pixel intensity**

- **The simplest approach is to simply use the coverage percentage as a scale factor for the object's intensity**
  - Creates non-linear transitions between pixels
  - Distance of the object from the pixel center is ignored
  - Box filter



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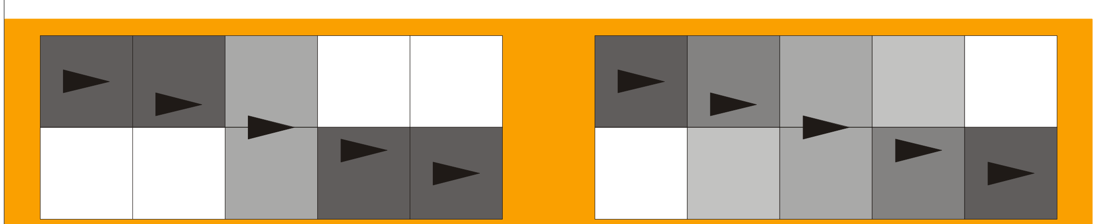
Anti-aliasing: Filtering (2)

- **For a given pixel, the contributions of objects in a neighborhood around the pixel must be combined using a weighted average**

- **The averaging method must satisfy several criteria**
  - This neighborhood is larger than 1 pixel
  - An object contributes less if it is farther away from the pixel center
  - The total contribution of an object to all affected pixels is constant



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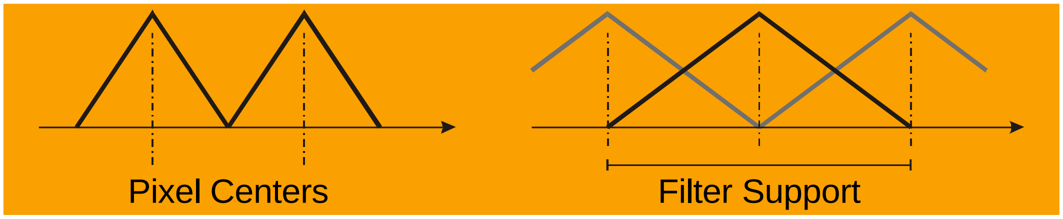
Anti-aliasing: Filtering (3)

- Filter shapes with a fall-off away from the pixel center and extending beyond the pixel borders satisfy these criteria



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Anti-aliasing: Filtering (4)

- Different filter shapes satisfy these criteria
  - Triangular filter, Gaussian filters, ...
- However the actual image quality still differs between these filters
  - In general the more complicated the filter, the better the results
- This observation is explained by sampling theory

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Sampling Theory: Overview

- Sampling theory investigates and describes the effects of sampling continuous signals
- Examples of signals
  - Time-variant, e.g. sound
  - Space-variant, e.g. images
  - One-dimensional, e.g. scanline
  - Two-dimensional, e.g. image
- The signal is considered either in the time/spatial domain of the frequency domain

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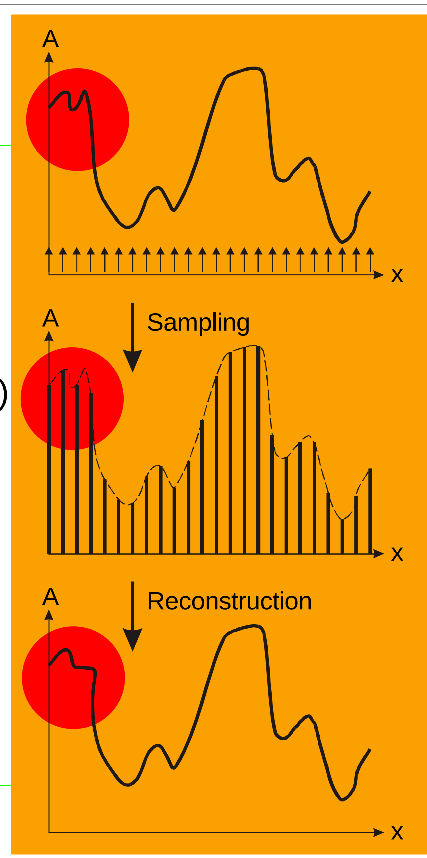
Sampling Theory: Sampling Process



- Signal sampled at intervals
  - The size of these intervals determines the sampling frequency
  - The signal is multiplied by a comb function, consisting of several pulses (a.k.a. Dirac function or Delta function)
- The sampled signal consists of unconnected (discrete) values
- The reconstructed signal constructs a new signal that approximates the original signal
  - Reconstruction is done using a filter applied to the sampled signal

Sampling Theory: Scan Conversion

- **Scan Conversion samples the input geometry**
  - Determine the visible object and its attributes at the pixel center
  - Pixel centers form a two-dimensional array of Delta functions

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Sampling Theory: Frequency Domain

- **Fourier Analysis allows to decompose a signal into a mix of contributing sine waves**
  - Each sine wave has amplitude and phase
  - For periodic signals:
    Fourier series, i.e. (infinite) sum of discrete frequencies
  - For aperiodic signals:
    Fourier transformation, i.e. (infinite) integral various frequencies
- **The total of all frequencies forming a signal is called the spectrum**

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Sampling Theory: Notation

- **We denote the signal with lower case letters**
  - For example, *f(x)* or *g(x,y)*
- **The Fourier transform is shown in capital letters**
  - For example, *F(u)* or *G(u,v)*
  - The variable *u* is the frequency

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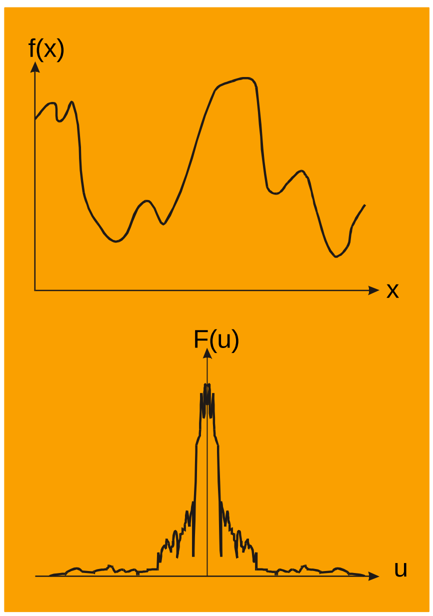
Sampling Theory: Signal and Spectrum

- **Fourier transformation connects signal and frequency domain**
  - Fourier transform returns amplitude and phase
  - Often, only the amplitude spectrum is of interest
  - DC value is F(0)
- **Typically spectrum falls off rapidly towards high frequencies**
  - Higher frequencies indicate higher energy



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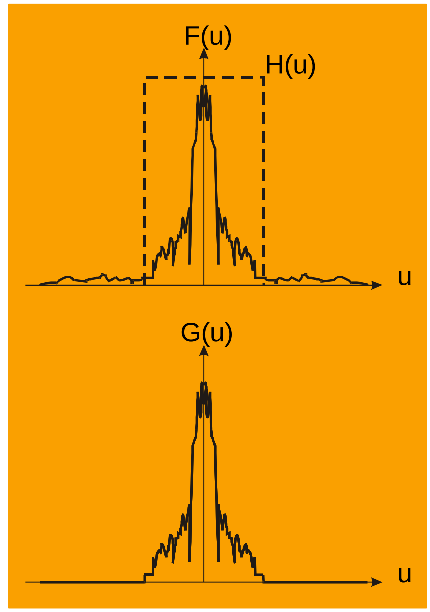
Sampling Theory: Filters

- **A Filter modifies the frequency spectrum**
  - Scales every component of the spectrum
  - $G(u) = F(u) * H(u)$
- **Several filters are frequently used**
  - Low-pass, eliminate high frequencies
  - High-pass, eliminate/reduce low frequencies
  - Band-pass, attenuate all frequencies outside a certain range



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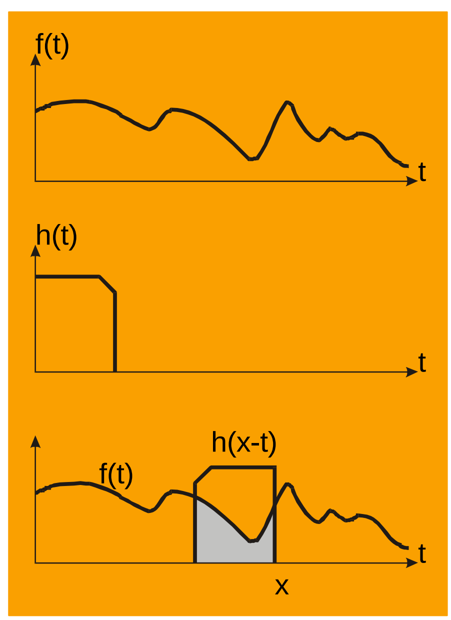
Sampling Theory: Convolution (1)

- **Fourier transformation relates multiplication in one domain with convolution in the other domain**
- **Convolution of signal *f* and filter *h* at a point *x* is the product of *f* and *h* centered at *x*.**

$$g(x) = f(x) * h(x) = \int_{-\infty}^{\infty} f(t) \cdot h(x-t) \cdot dt$$



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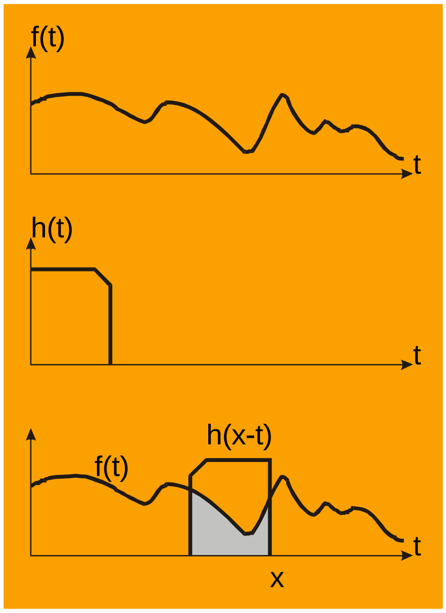
Sampling Theory: Convolution (2)

- Convolution computes an average of the signal *f* around *x* weighted by the filter function *h*



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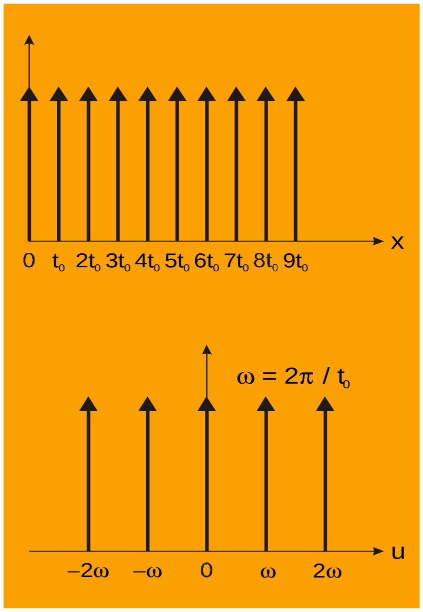
Sampling Theory: Sampling (1)

- Sampling is multiplying the original signal with a comb function
- This corresponds to a convolution of the signal with Fourier transform of the comb function.
- The Fourier transform of a comb function is another comb function
  - The distance between the Dirac pulses is determined by the sampling frequency



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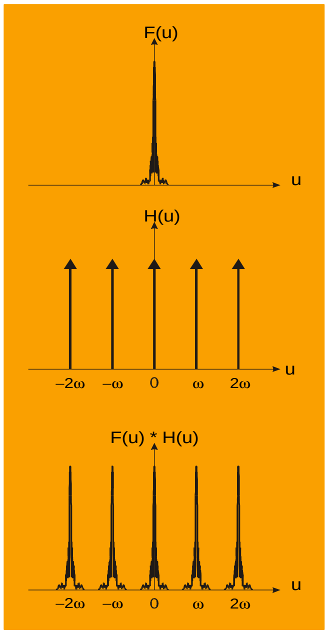
Sampling Theory: Sampling (2)

- Convolving the signal with a comb function replicates the spectrum of the signal centered around the Dirac pulses.
- If the sampling frequency is too low, the replicated spectra overlap. This generates aliasing.



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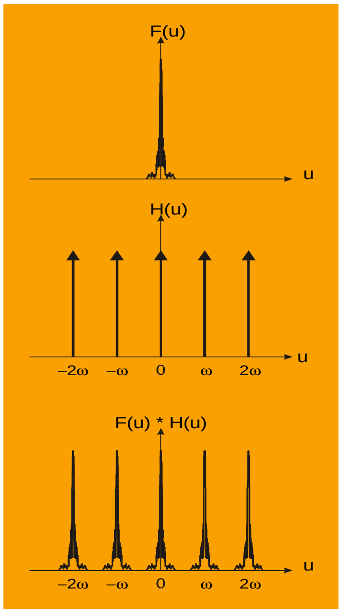
Sampling Theory: Nyquist Frequency

- Nyquist frequency is the minimum sampling frequency where spectra do not overlap
- Therefore:

$$f_0 = \frac{1}{t_0} \geq 2 \cdot f_{\max}$$



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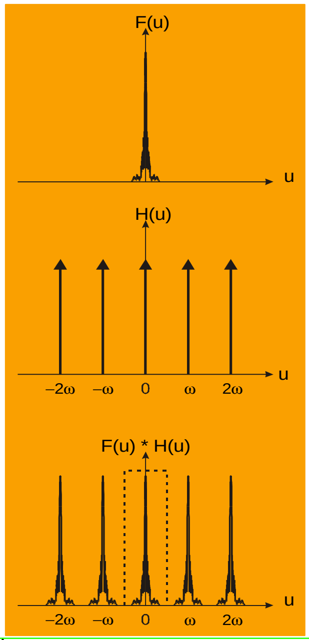
Sampling Theory: Low-pass Filter (1)

- In order to eliminate the extra copies of the spectrum, a low-pass filter is applied.
- If the copies of the spectrum do not overlap, the signal can be fully reconstructed
- Otherwise, the signal is only approximated
  - High frequencies are lost and the signal appears blurred



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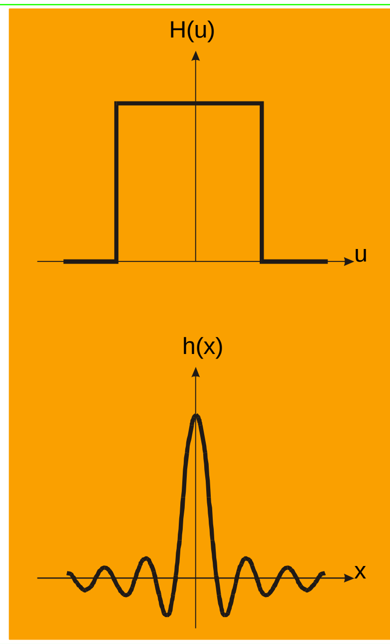
Sampling Theory: Low-pass Filter (2)

- Filtering
  - Multiplication in the frequency domain
  - Convolution in spatial domain
- Ideal low-pass filter
  - A.k.a. box filter
  - Sharp cut-off frequency
  - Corresponds to sinc function in the spatial domain
  - sinc(x) = sin(x) / x



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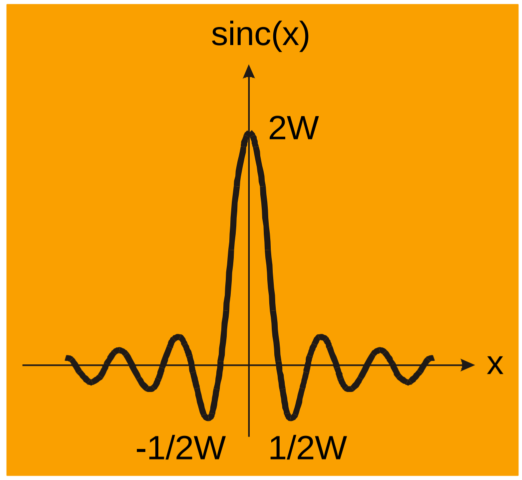
Sampling Theory: Sinc function

- **Amplitude *A* and zero crossings of the sinc function are determined by the sampling frequency *W***
  - A = 2W will preserve the energy of the signal
  - Lower sampling frequency widens the sinc function and reduces its amplitude



- **Sinc is problematic**
  - Very wide non-zero support
  - Negative lobes

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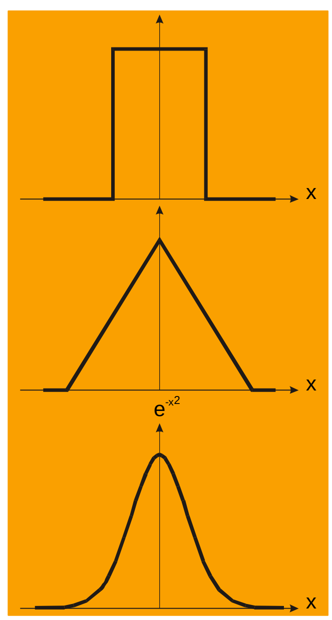
Sampling Theory: Other Filters (1)

- **Box filter**
  - Sinc in frequency domain
  - Wide non-zero, negative support
  - Unweighted average,
    very simple, but large errors
- **Triangular filter**
  - Sinc^2 in frequency domain
  - Smaller, positive support
  - Weighted average, fairly simple
- **Gaussian filter**
  - Gausian in frequency domain
  - Small, posititive support
  - Better weighted average
  - Computationally expensive



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Sampling Theory: Other Filters (2)

- **Windowed filters**
  - E.g. windowed sinc function, i.e.

$$sw(x) = \begin{cases} \mathrm{sinc}(x) & \text{if } |x| < const. \\ 0 & \phantom{\text{if }} |x| \geq const. \end{cases}$$

- **Requirements for any filter functions**
  - The integral over the filter function is 1.
    This ensures that the signal is not attenuated or amplified
  - The filter function should have finite support in the spatial domain.
    This makes it practical to compute the filter function.

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Sampling Theory: Summary

- **Scan conversion forms a sampling process with subsequent reconstruction**
- **Sampling theory tells us that reconstruction of a sample signal can only be accomplished if the sampling frequency is above the Nyquist frequency**
  - Then the copies of the signals spectrum do not overlap
  - To meet this condition, the signal must be band-limited
- **Reconstruction is accomplished with a low-pass filter**
  - Low-pass filtering means to compute a weighted average in the spatial domain
  - The spatial domain is larger than one pixel !
  - Different low-pass filters can be used.

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Anti-aliasing: Implementation

- **Proper filtering of the rendered primitives can be difficult and computationally expensive**
- **Various techniques approximate the proper calculation of the area contributions**
  - Super-sampling
  - Alpha channel for image compositing
- **Additional problems arise if hidden-surface removal is combined with anti-aliasing**
  - How much does the object cover the pixel ?
  - How much of the object is visible in the pixel ?

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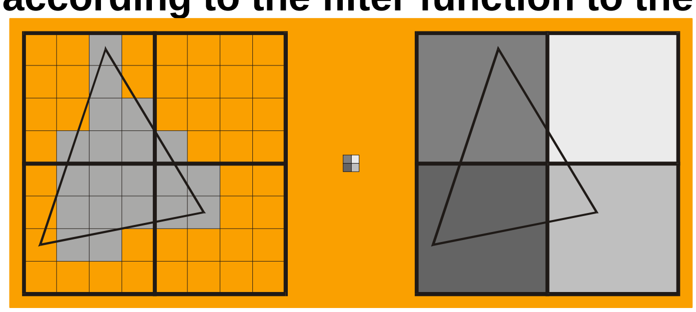
Anti-aliasing: Super-sampling (1)

- **The area covered by the object is computed by point sampling the pixel itself**
  - Sample locations are known as sub-pixels
  - Sub-pixel coverage approximates the true coverage
  - Simple to compute, applicable to all primitive types
- **Filtering weights and combines the sub-pixel values according to the filter function to the final pixel value**



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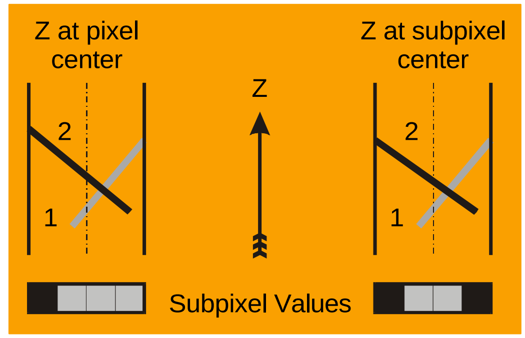
Anti-aliasing: Super-sampling (2)

- **Determine visibility only at pixel center**
  - Creates wrong results if visibility changes in the pixel
  - Requires only standard z-buffer and frame buffer
- **Determine visibility at every sub-pixel**
  - Proper resolution of visibility within the pixel
  - Adjust depth value to sub-pixel location
  - Requires high-resolution z-buffer for sub-pixel color / z



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Anti-aliasing: Compositing (1)

- **Compositing was developed for combining images**
  - Images are combined pixel by pixel
  - First described by Porter & Duff in 1984
- **At every pixel we store in the alpha channel the current coverage information**
- **For a new fragment we compute new color and alpha information based on pixel and fragment color/alpha**
- **We will now look at compositing two fragements, each of which has only one edge crossing its pixel area**
  - More edges per pixel are rare cases and not treated explicitly
  - No edges are covered by setting $\alpha = 1$

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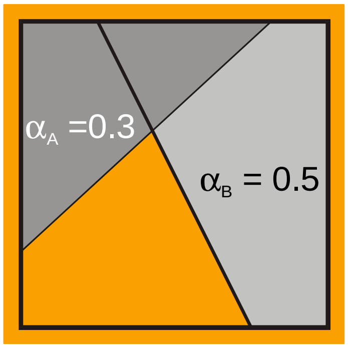
Anti-aliasing: Compositing (2)

- **The alpha value does not provide information about how the object is oriented within a pixel**
  - There is no clear definition on how to combine current pixel value and new fragment value
  - Several possibilities for how two fragments might interact
- **For image synthesis and anti-aliasing only one is relevant: A over B**
  - See Foley et al. chapter 17.6 for other operations



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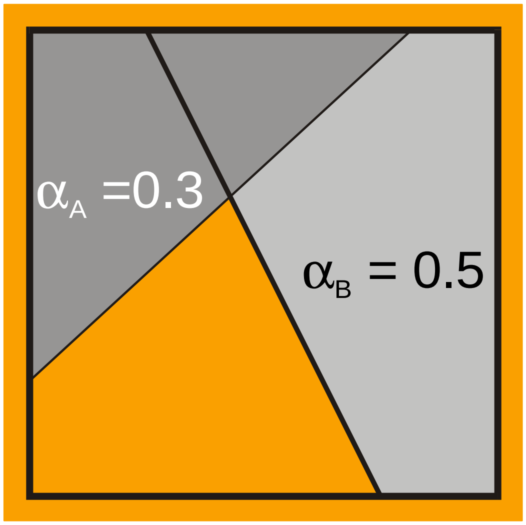
Anti-aliasing: Compositing (3)

- **A over B**
  - Determine which objects is in front of the other (visibility)
  - Both fragments contribute
  - Assume random orientation of edges within the pixel
  - Then, on average $(1-\alpha_A)$ of fragment B is visible

$$C = a_A \cdot A + (1 - a_A) \cdot a_B \cdot B$$
$$a = (1 - a_A) \cdot (1 - a_B)$$



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Anti-aliasing: Compositing (4)

- **Notice, that the fragment colors A and B are always used weighted by the coverage values a**

$$C = a_A \cdot A + (1 - a_A) \cdot a_B \cdot B$$
$$a = (1 - a_A) \cdot (1 - a_B)$$

- **To avoid computing the term a*A at every pixel, colors are stored premultiplied by a**
  - Instead of (R,G,B,α) we store (αR,αG,αB,α)

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Anti-aliasing: OpenGL (1)

- **Anti-aliasing in OpenGL may differ for different OpenGL implementations**
  - Quality of anti-aliasing controlled via "hints" (glHint)
- **Point and Line anti-aliasing**
  - glEnable(GL_POINT_SMOOTH) + glEnable(GL_LINE_SMOOTH)
- **Polygon anti-aliasing**
  - If drawn as points or lines, point/line anti-aliasing applies
  - Otherwise, glEnable(GL_POLYGON_SMOOTH). This will generate coverage information in a fragment's alpha value
  - Then setup the alpha-blending function to blend between incoming fragment and stored pixel value

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Anti-aliasing: OpenGL (2)

- Supersampling is supported in OpenGL via the Accumulation Buffer
- The accumulation buffer is a very deep frame
- Successive rendering passes are accumulated in the accumulation buffer
- At the end the pixel values are divided by the number rendering passes (averaging)
- Supersampling is implemented by jittering the scene position slightly (subpixel distance) between passes

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Anti-aliasing: Summary

- **Aliasing result of under-sampling the primitives**
  - Geometric primitives introduce infinite frequencies along edges
- **Sampling theory indicates that the signal must be band-limited before sampling to allow full reconstruction of the signal**
  - The ideal low-pass filter is hard to implement
  - Approximations mean the computation of a weighted average of the pixel area covered by a primitive (area sampling)
- **Area sampling is hard to perform accurately**
  - Supersampling and compositing approximate correct area sampling and resolution of visibility between several fragments partially covering into a pixel

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VRML

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VRML

- **VRML = Virtual Reality Modeling Language**
  - Derived from SGI's OpenInventor
  - Version 2.0 has been adopted by ISO as VRML'97 standard
- **VRML was designed for definition, interaction and transmission of 3D models in a web-environment**
  - Based on a scene-graph model
  - Supports several non-graphics constructs to build virtual worlds, e.g. audio, event routing, customizable nodes (prototypes), concept of time, scripting interface
- **We will focus here on the graphics-specific elements of VRML, i.e. scene graphs and basic event processing**
  - Also see paper handed out in class

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VRML: Overview

- **Scenes are constructed by building a scene-graph**
  - Basically identical to the model hierarchies we discussed earlier
  - Different nodes represent objects, transformations, attributes and grouping semantics
  - More formally nodes are classified as geometry (shape) nodes, appearance nodes, geometric property nodes and grouping nodes
- **Each node has none, one or several fields that set relevant node parameters**
  - Each node field has a name and a default value
  - Fields not explicitely set will assume their default value

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VRML: Files

- **VRML files have the extension ".wrl" for "world"**
- **VRML files**
  - Very brief header
  - Description of the world

```
#VRML V2.0 utf8

Shape
{
 appearance Appearance
 {
  material Material
  {
   diffuseColor 1.0 0.0 0.0
   specularColor 1.0 1.0 1.0
   shininess 10
  }
 }

 geometry Cone
 {
  bottomRadius 1.0
  height 2.0
 }
}
```


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VRML: Nodes

- **Nodes compose the scene graph describing the world**

- **Syntax**
  - Unnamed nodes:
    <nodeType> { <body>}
  - Named nodes:
    DEF <name> <nodeType> {<body>}
  - Named nodes can be instantiated anywhere a node is expected:
    USE <name>
  - The body of a node specifies the values of its fields and events it can send and receive

```
#VRML V2.0 utf8

Shape
{
 appearance Appearance
 {
  material Material
  {
   diffuseColor 1.0 0.0 0.0
   specularColor 1.0 1.0 1.0
   shininess 10
  }
 }

 geometry Cone
 {
  bottomRadius 1.0
  height 2.0
 }
}
```


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VRML: Fields

- **Fields set a node's parameters**
  - All fields have default values
  - Default values are used if no specific value is assigned

- **Syntax**
  - Single valued field (prefix SF)
    <fieldName> <fieldValue>
  - Multi-valued field (prefix MF)
    <fieldName> [<fieldValues>]
  - Multiple values are separated by commas
  - The brackets may be omitted if only one value is assigned


```
#VRML V2.0 utf8

Shape
{
 appearance Appearance
 {
  material Material
  {
   diffuseColor 1.0 0.0 0.0
   specularColor 1.0 1.0 1.0
   shininess 10
  }
 }

 geometry Cone
 {
  bottomRadius 1.0
  height 2.0
 }
}
```


Computer Graphics – Week 8

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VRML: Field Types

- **Every field can only assume values of a specific type**
- **Types include**
  - Bool, Int32, Float, Vec2f, Vec3f, String,
  - Color, Image, Time, Rotation
  - Node
- **Most node types are available as single-valued and multi-valued versions (except Bool and Image)**

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VRML: Node Types (1)

- **Shapes and Geometry**
  - Box, Cone, Coordinate, Cylinder, ElevationGrid, Extrusion, IndexedFaceSet, IndexedLineSet, Normal, PointSet, Shape, Sphere, Text
- **Appearance**
  - Appearance, Color, FontStyle, ImageTexture, Material, MovieTexture, PixelTexture, TextureCoordinate, TextureTransform
- **Grouping**
  - Anchor, Billboard, Collision, Group, Inline, LOD, Switch, Transform
- **Environment**
  - AudioClip, Background, DirctionalLight, Fog, PointLight, Sound, Spotlight

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VRML: Node Types (2)

- **Viewing**
  - NavigationInfo, Viewpoint
- **Animation (Interpolators)**
  - ColorInterpolator, CoordinateInterpolator, NormalInterpolator, OrientationInterpolator, PositionInterpolator, ScalarInterpolator, TimeSensor
- **Interaction (Sensors)**
  - CylinderSensor, PlaneSensor, ProximitySensor, SphereSensor, TouchSensor, VisibilitySensor
- **Miscellaneous**
  - Script, WorlInfo

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VRML: Shape and Geometry Nodes (1)

- **Shape Node**
  - Container node to collect geometry and appearance data
  - Use various other nodes to specify these fields
- **3D Primitives**
  - Box: axis-alined box with specified dimensions
  - Cone: cone around Y axis, centered at origin
  - Sphere: obvious

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VRML: Shape and Geometry Nodes (2)

- **Indexed Face Set**
  - Used to build shapes as a collection of planar polygons
  - Polygons are defined from indices into arrays of vertices, colors, normals, and texture coordinates
- **The node contains at least**
  - a list of vertex coordinates (field 'coord')
  - a list of vertex indices defining the faces (field 'coordIndex')
- **Optionally, attributes can be defined at the vertices**
  - Colors, normals, texture coordinates
- **IndexedLineSet is a similar construct for constructing a collection of lines**

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VRML: Shape and Geometry Nodes (3)

- **Example: Pyramid**

```
#VRML V2.0 utf8

Shape
{     geometry IndexedFaceSet
      {     coord Coordinate
            {     point
                  [ -1 -1 0,   1 -1 0,  1  1 0,  -1  1 0,   0  0 2
                  ]
            }
            color Color
            {     color
                  [ 1 0 0, 1 0 1,  0 0 1,    0 1 1, 1 1 0
                  ]
            }
            colorPerVertex TRUE
            coordIndex
            [ 0 3 2 1 -1,   # bottom
             0 1 4 -1,       1 2 4 -1,  2 3 4 -1,  3 0 4 -1
            ]
      }
```


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VRML: Grouping Nodes (1)

- **Simplest one is Group**
  - Collects several children into a group
  - Field 'children' contains those node
- **Transformation node is similar to Group node**
  - Scales, rotates and translates (in that order) its children
- **Billboard**
  - Always orients the local Z-axis to point to the viewer by rotating all children around specified axis
  - Supports the display of objects that always face the viewer, e.g. "flat trees", signs, etc.

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VRML: Grouping Nodes (2)

- **Anchor node**
  - Loads another URL when the user clicks on any of the children nodes
  - Replaces the current world
- **Inline node**
  - Reads content of another URL and merges its nodes into the current world (similar to #include in C preprocessor)
  - Does not replace the current world

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VRML: Grouping Nodes (3)

- **Switch**
  - Selects one amongst its children for display
  - The 'whichChoice' field can be changed via events
  - Useful e.g. for simple animation or state changes
- **LOD (level of detail)**
  - Selects from several representations (levels) of the same object
  - Switching depends on the distance from the viewer
  - Switching thresholds are specified for each level
  - Useful to increase rendering efficiency by displaying simpler representation for distant objects

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VRML: Appearance Nodes

- **Appearance nodes are container nodes for various surface properties**
  - Materials
  - Textures
- **Textures are specified as images**
  - PixelTexture: specifies the image in the VRML file
  - ImageTexture: specifies the image by reference to an external file
  - MovieTexture: time dependent texture loaded from an external MPEG-1 file

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VRML: Lighting Models and Materials

- **Lighting models and material properties are very similar to OpenGL**
  - Lights are placed in the scene like regular objects. The subject to standard transformations
  - Check out the following nodes:
    DirectionalLight, PointLight, SpotLight, Fog, and Material

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VRML: Viewing and Navigation

- **Viewpoint selection and navigation is primarily controlled by the browser**

- **Viewpoints can be specified in the VRML file**
  - Viewpoint node allows to predefine several nodes
  - Viewpoints can be selected by the browser
  - Viewpoints can manipulated automatically by changing the parent transformation node

- **Navigation specifies how the browser manipulates the viewpoint**
  - NavigationInfo node supports various modes, e.g. WALK, FLY, EXAMINE

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VRML: Authoring and Viewing

- **Obviously, creating VRML files using a text editor is (at best) inconvenient**
  - The text-based format makes it easy to generate VRML through authoring applications, e.g. 3D editors, scientific visualizations etc.
- **VRML files are viewable through various tools**
- **Most popular viewers are known as VRML browser**
  - Plug-ins available for most Web-browser

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Summary

- **Aliasing and Anti-aliasing**
  - Route cause is sampling below Nyquist frequency
  - Area-sampling is an implementation of low-pass filtering the image
  - Super-sampling and compositing
- **VRML**
  - Basic concepts
  - Syntactical elements
  - We have not covered advanced VRML features

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Homework

- **Prepare for the midterm exam**
- **The exam is a closed book exam. You are allowed to bring 1 letter-sized sheet with notes.**
- **Read the lecture notes and the corresponding chapters in the textbook**
  - You must demonstrate understand of the material and can apply it
  - Fully understand the polygon raster pipeline, i.e. sequence, function, and algorithms
  - You should be able to apply algorithms etc. Except in very simple cases, you do not need to derive formulae.
  - Exam questions will query knowledge, understanding and ability to use what you learned

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Assignment

- **Create a VRML cityscape**
  - Streets, buildings, cars, people, trees, ...
- **Although not the preferred way, create the world from scratch, i.e. using a text editor**
- **There are very few requirements**
- **So ...**

  go out, be wild, have some fun
- **And ...**

  come back with a cool VRML world

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Next Week ...

- **Spring break !!!**

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