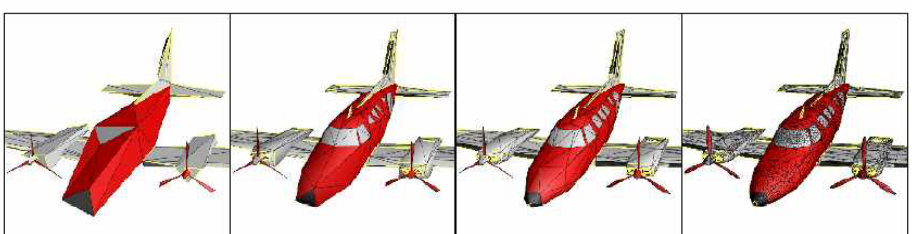
Multi-Resolution Visualization (MRV)

Fall 2009

Jing Yang

MRV Motivation (1)

- Limited computational resources



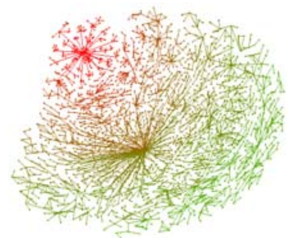
(a) Base mesh M^0 (150 faces) (b) Mesh M^{175} (500 faces) (c) Mesh M^{425} (1,000 faces) (d) Original $\hat{M}=M^n$ (13,546 faces)

Example: Internet-Based Server 3D applications using progressive meshes [Hop96]

MRV Motivation (2)

- Restricted cognitive resources of human viewers

(a)



(b)

Example: A graph that contains 87,931 vertices and 87,930 edges [GKN04]

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More Examples

- Examine several examples in multiple disciplines
  - Image processing
  - 3-D surface rendering
  - Volume rendering
  - Flow visualization

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Paper 1: Efficient Support for Interactive Service in Multi-resolution VOD Systems (K. Law, J. Lui, and L. Golubchik. 1999)

- Background: Video-On-Demand services
  - Allow users to tailor video playback quality
  - Provide VCR operations such as fast-forward
- Challenges:
  - Storing multiple copies of a video in different resolutions wastes space
  - VCR may cause additional I/O, network bandwidth and system buffer

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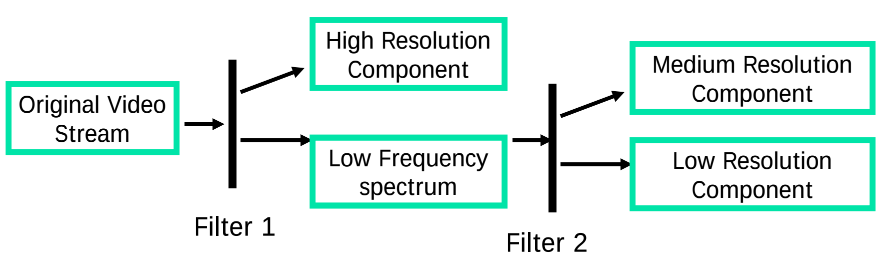
Paper 1: Efficient Support for Interactive Service in Multiresolution VOD Systems (K. Law, J. Lui, and L. Golubchik. 1999)

- Multi-resolution technique used: *sub-band coding*



An example of sub-band decomposition

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Paper 1: Efficient Support for Interactive Service in Multiresolution VOD Systems (K. Law, J. Lui, and L. Golubchik. 1999)

- Features
  - Limited I/O and network resources are motivations.
  - Data needs to be pre-processed.
  - Users can control the resolution.
  - The more details, the better.
  - High resolution = Low resolution + difference

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Paper 1: Efficient Support for Interactive Service in Multiresolution VOD Systems (K. Law, J. Lui, and L. Golubchik. 1999)

- Feature preservation from a higher resolution to a lower one:
  - Reserve low frequency spectrum
  - Filter out high frequency spectrum
- Resolution control:
  - VCR
  - Playback quality setting

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Paper 2: Efficient Compression and Rendering of Multi-Resolution Meshes
(Z. Karni, A. Bogomjakov, and C. Gotsman. 2002)

- Background: Internet-based server 3D applications
  - Require fast transmission of a geometric model
  - Require fast rendering at the client
- Challenge:
  - A large high resolution model may not be transmitted to the client on time.

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Paper 2: Efficient Compression and Rendering of Multi-Resolution Meshes
(Z. Karni, A. Bogomjakov, and C. Gotsman. 2002)

- Multi-resolution technique used: *progressive mesh coding*
  - Reconstruct a rough resolution of the mesh using a small number of bits received
  - Gradually refine the mesh as more bits arrived

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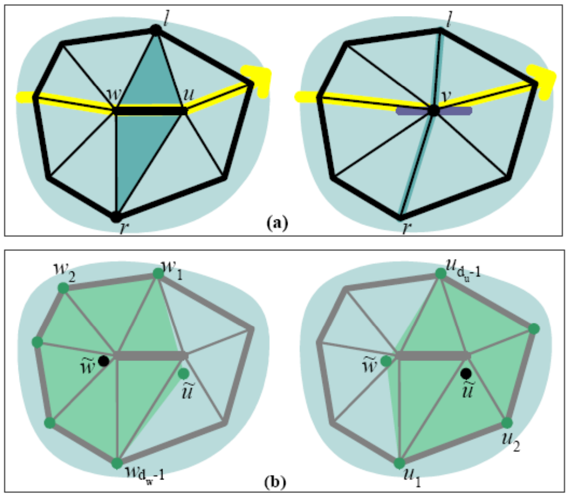
Paper 2: Efficient Compression and Rendering of Multi-Resolution Meshes
(Z. Karni, A. Bogomjakov, and C. Gotsman. 2002)



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Paper 2: Efficient Compression and Rendering of Multi-Resolution Meshes
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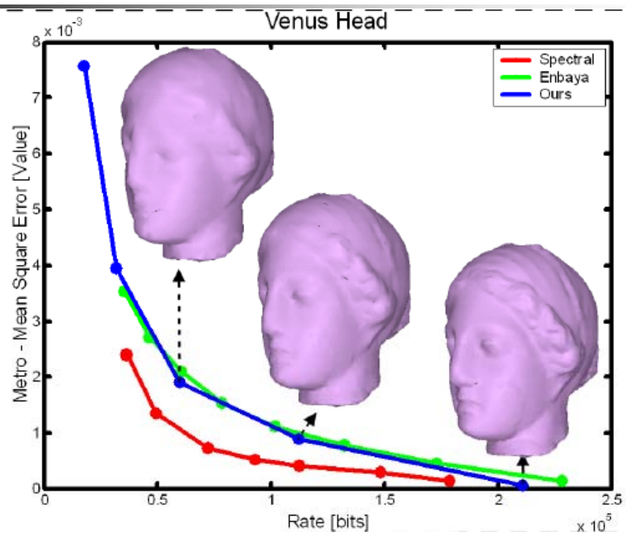

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Paper 2: Efficient Compression and Rendering of Multi-Resolution Meshes
(Z. Karni, A. Bogomjakov, and C. Gotsman. 2002)

- Features
  - Limited I/O and network resources are motivations.
  - Data needs to be pre-processed.
  - Level Of Detail (LOD) can be changed locally (within sub-region).
  - Users has no LOD control other than stopping the refinement.
  - Resolution change gradually. No surprise for users.

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Paper 2: Efficient Compression and Rendering of Multi-Resolution Meshes
(Z. Karni, A. Bogomjakov, and C. Gotsman. 2002)

- Feature preservation from a higher resolution to a lower one:
  - Adjacent vertices in a special sequence are collapsed into their centroid.
- Resolution control:
  - A user can stop the refinement when the mesh is good enough.

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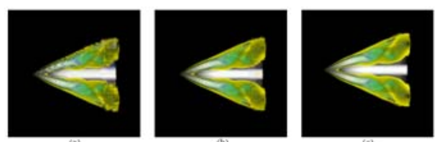
Paper 3: Time-Critical Multiresolution Volume Rendering using 3D Texture Mapping Hardware (X. Li and H. Shen. 2002)

- Background: time-critical applications
  - Example: virtual surgery
  - Precise rendering time control is crucial
- Challenges:
  - Rendering may not be fast enough for large volume dataset. So hierarchical rendering is used to trade off between quality and speed
  - How to select proper LOD at run time?



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Paper 3: Time-Critical Multiresolution Volume Rendering using 3D Texture Mapping Hardware (X. Li and H. Shen. 2002)

- Solution: Automatic LOD selection
  - Control frame rate precisely
  - Control time distribution among different sub-regions
- Pre-processing: Hierarchical volume structure
  - The entire volume is divided into subvolumes.
  - Multiple resolutions are created for each subvolume.
  - Each subvolume is assigned an importance value.

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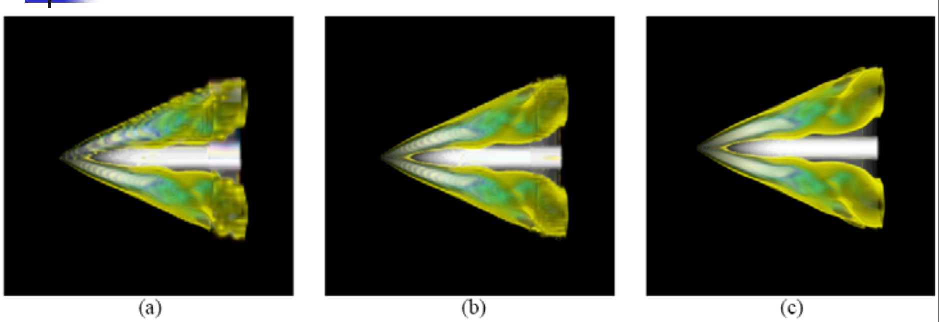
Paper 3: Time-Critical Multiresolution Volume Rendering using 3D Texture Mapping Hardware (X. Li and H. Shen. 2002)

- Run-time LOD selection:
  - Subvolumes are rendering one by one.
  - Available rendering time is distributed among subvolumes to be rendered according to their importance values.
  - Rendering time for each LOD is predicted from statistic of previous rendering.
  - For each subvolume, a LOD whose predicted rendering time is closest to the assigned time is selected.

Paper 3: Time-Critical Multiresolution Volume Rendering using 3D Texture Mapping Hardware (X. Li and H. Shen. 2002)

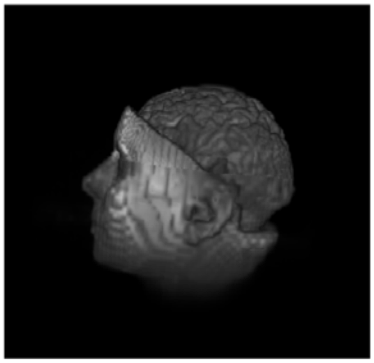


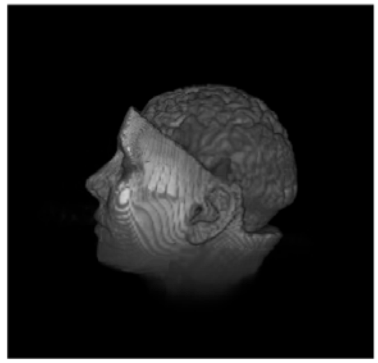
(a) Without importance parameter

(b) Use opacity as importance parameter – More time to render less transparent areas

(c) Full resolution display

Paper 3: Time-Critical Multiresolution Volume Rendering using 3D Texture Mapping Hardware (X. Li and H. Shen. 2002)


(a)


(b)

(a) Without importance parameter

(b) Use view distance and projection areas as importance parameters

Paper 3: Time-Critical Multiresolution Volume Rendering using 3D Texture Mapping Hardware (X. Li and H. Shen. 2002)

- Features
  - Motivated by limited computational resource.
  - Data needs to be pre-processed.
  - Different regions can have different LODs.
  - Regions of users' interest are displayed in more detail.
  - Precise time control mechanism
  - Pre-load different LODs as texture objects

Paper 3: Time-Critical Multiresolution Volume Rendering using 3D Texture Mapping Hardware (X. Li and H. Shen. 2002)

- Feature preservation from a higher resolution to a lower one:
  - A lower resolution is generated by averaging adjacent voxels in the higher resolution.
- Resolution control:
  - Importance values
  - User preferred frame rate

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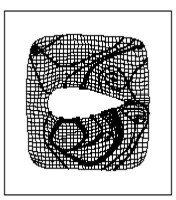
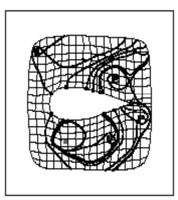
Paper 4: Wavelets over Curvilinear Grids (G.M. Nielson, I.-H. Jung, and J. Sung. 1998)

- Motivation:

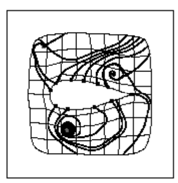
  High level details often clutter a 2-D flow display
- Approach: wavelet multi-resolution display



Original display



Display with reduced resolution



Resolution is further reduced

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Paper 4: Wavelets over Curvilinear Grids
(G.M. Nielson, I.-H. Jung, and J. Sung. 1998)

- Solution: a multi-resolution model for 2-D flow display
  - Lower resolutions eliminate high order details while reserves major trends
  - Resolution can be changed locally
  - Zoom in and out can be combined with LOD changes

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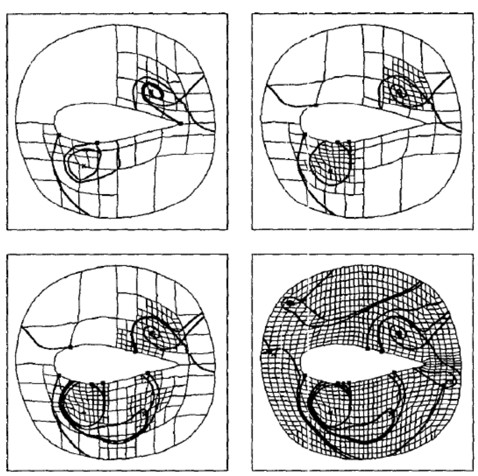
Paper 4: Wavelets over Curvilinear Grids
(G.M. Nielson, I.-H. Jung, and J. Sung. 1998)



Different Local Resolutions

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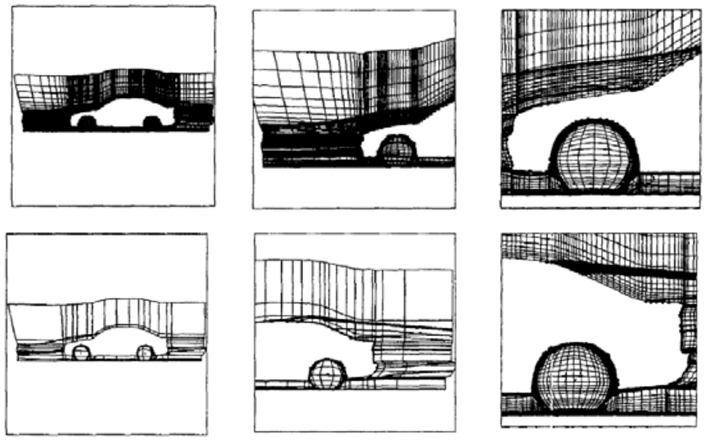
Paper 4: Wavelets over Curvilinear Grids
(G.M. Nielson, I.-H. Jung, and J. Sung. 1998)



Different Zooming Approaches

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Paper 4: Wavelets over Curvilinear Grids
(G.M. Nielson, I.-H. Jung, and J. Sung. 1998)

- Features
  - Motivated by the clutter problem.
  - Data needs to be pre-processed.
  - Different regions can have different LODs.
  - Users can interactively change LODs.
  - High resolution = Low resolution + difference
  - Zooming

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Paper 4: Wavelets over Curvilinear Grids
(G.M. Nielson, I.-H. Jung, and J. Sung. 1998)

- Feature preservation from a higher resolution to a lower one:
  - A lower resolution is abstracted from a higher resolution using wavelet decomposition functions.
- Resolution control:
  - LODs of different regions can be set manually.

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MRV Motivation Summary

- Limited computational resources
  - Network, processing resource, storage
- Restricted cognitive resources of human viewers
  Different cases
  - The more detailed, the better
  - Less detail is preferred
- Other reason:
  - Privacy

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A General Framework for Multi-Resolution Visualization (MRV)

- Large data sets are common nowadays.
- MRV systems are widely used to handle large data sets, they share many common features.
- The framework summarizes these common features.

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Semantic Abstraction Model

- Three levels of the abstraction model [SZ98]
  - perception of the world
  - memorization of the perception
  - description of the memories
- Reasoning context R = (P(W), S, L) [SZ98]
  - World W: the world where the concrete objects reside.
  - Perception, View P(W): the perception that an observer has of the world.
  - Structure S: an extensional representation of the perceived world
  - Language L: a language that allows reasoning about the perceived world and communication with others

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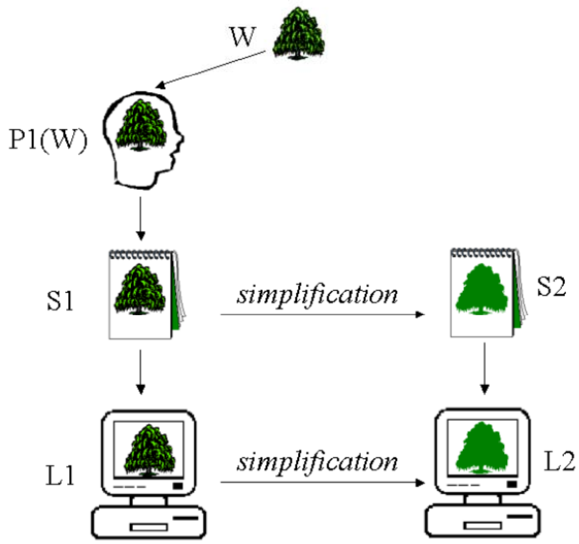
The MRV Model



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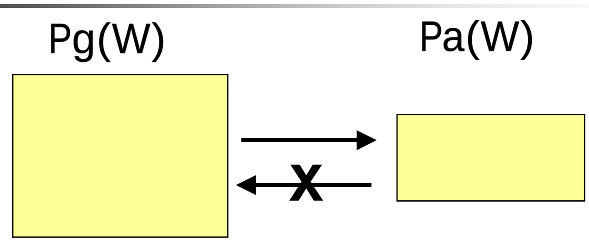
Abstraction and Simplification [SZ98]



- An abstraction is a functional mapping: Pg(W) → Pa(W)
- Abstraction is a mapping between the views (perceptions) of the world
- The modifications of the structures and the languages, which are called simplification, are side effects that are necessary for describing what happens at the level of the perceived world

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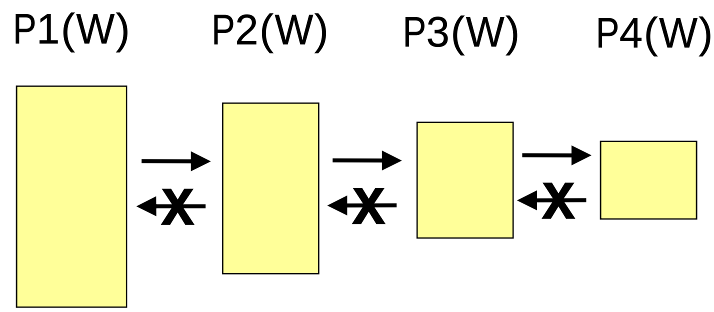
Abstraction Hierarchy



Level of detail (LOD):

LOD of P1(W) > LOD of P2(W) > LOD of P3(W) > LOD of P4(W)

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Definition of MRV System

- MRV system
  - A visualization system that visually represents abstraction hierarchies of views and allows users to interactively navigate among the views
- Essential features of a MRV system:
  - Abstraction hierarchies of views
    - Problem: they are often not provided to the MVT systems
  - Interactive visualization

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General Framework for MRV

- View simulation - a MRV system simulates abstraction hierarchies of views through simplification if they are not provided
  - Simplification operators
  - Simplification operands (spaces)
- Interactive visualization - a MRV system visually presents the views and allows users to interactively navigate among them
  - MRV interfaces
  - MRV interactions

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Simplification Overview

Operators

- Sampling
- Aggregation
  - Clustering
  - Histograms
- Approximation
  - Proximity positioning
  - Wavelet
- Generalization

Operands

- Data space (structure level)
  - Data item space
  - Dimension space
  - Topology space
- Visualization space (language level)
  - Visualization structure space
  - Visual encoding space
  - Screen space

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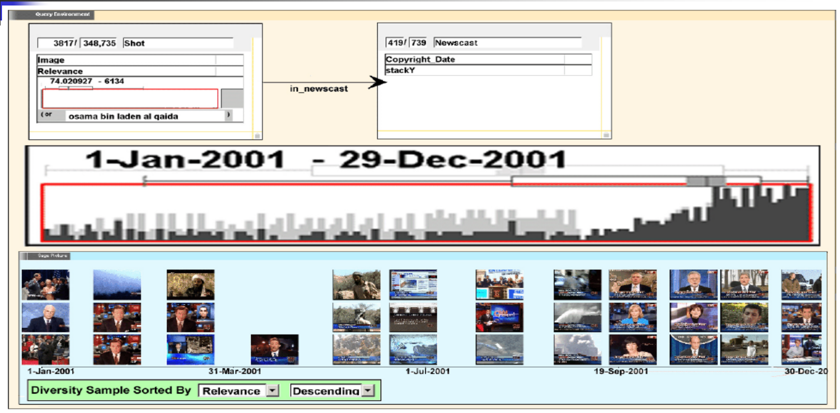
Sampling Operator

- Sampling - the process of selecting some part of a population to observe so that one may estimate something about the whole population [Tho92].

Sampling in MRV Application

Example: query results to a video library are represented using a collage of representative key frames [DCHW03]. Occlusion happens in this display. This figure is used without authors' permission.

Sampling in MRV Application



Sampling is used to reduce the number of key frames shown in the display to make sure that there is no occlusion [DCHW03]. This figure is used without authors' permission.

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Paper: By Chance - Enhancing Interaction with Large Data Sets through Statistical Sampling (A. Dix and G. Ellis. 2002)

- Goal: summarize the relationships between random sampling and visualization.
- Why random sampling benefits visualization?
  - Fasten interactions
  - Reduce clutter
- Why random sampling is acceptable in visualization?
  - Gestalt visual processing often depends on approximate rather than exact properties of data.
  - A dataset itself is often a sample from the real world.

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Paper: By Chance - Enhancing Interaction with Large Data Sets through Statistical Sampling (A. Dix and G. Ellis. 2002)

- When random sampling can be applied in visualization?
  - Visualization based on aggregate or summary statistics can use sampled data to give approximations
  - Visualization containing points or lines that could saturate the display can use sampled data to avoid saturation and reveal features and relationships.
  - Sampling can be used to reduce the data set to a size that allows detailed visualization such as thumbnails of individual items.

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Paper: By Chance - Enhancing Interaction with Large Data Sets through Statistical Sampling (A. Dix and G. Ellis. 2002)

- Information loss:
  - Measure - how the visualization obtained from the sample is distinguishable from that obtained from the full data set.
  - Users should be aware of the information loss – use error bars, blurred edges, and ragged displays
- Sampling rate changes:
  - Smooth transitions between different resolutions are beneficial
  - Example: when sampling rate increases, keep the data points in the previous view on the screen.

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Paper: By Chance - Enhancing Interaction with Large Data Sets through Statistical Sampling (A. Dix and G. Ellis. 2002)

Example - Astral Telescope Visualizer

- Users can interactively change the zoom value of a 2D scatterplot display.
- The sampling rate increases automatically with the increase of the square of the zoom value.
- Extra points are sampled and previously sampled data points in the zoomed area are remained after a zoom in operation.
- It permits smooth transition between sampling rates.

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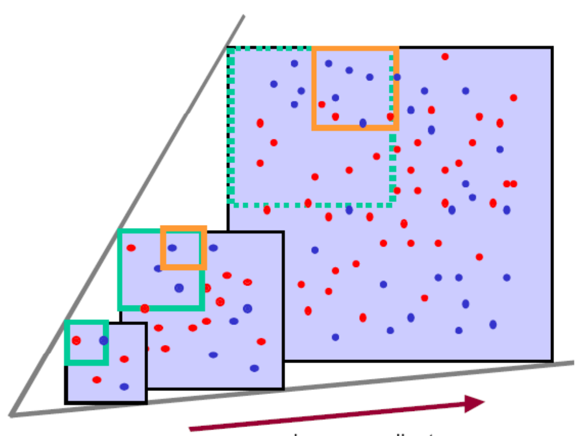
Astral Telescope Visualizer



Astral Telescope Visualiser

By Chance - Enhancing Interaction with Large Data Sets through Statistical Sampling (A. Dix and G. Ellis. 2002)

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Measures of Information Loss

- Standard error (sqare root of the variance) of the unbiased estimator
- Cluster loss
- Group loss
- Average squared relative error
- How the visualization obtained from the sample is distinguishable from that obtained from the full data set.

Aggregation Operators

- Aggregation - a simplification in which a relationship between objects is regarded as a higher level object [SS77].
- Aggregation operators include:
  - Clustering
  - Histograms
  - Other operators

Clustering Operators

- Clustering - a division of data into groups of similar objects. Each group, called a cluster, consists of objects that are similar among themselves and dissimilar to objects of other groups [Ber02].
- Why use clustering in visualization?
  - Reduce number of visual elements on screen
  - Explicitly reveal hidden patterns to viewers.

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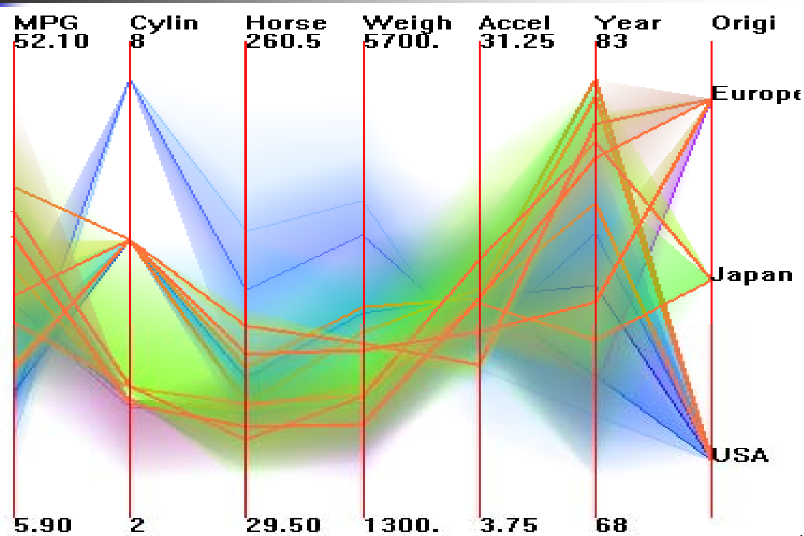
Hierarchical Clustering in MV Vis



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Histogram Operators

- A histogram partitions the data space into buckets. In each bucket, the data distribution is often assumed uniform and recorded using simple statistic data.
  - The distribution of each bucket can also be approximated using more complex functions and statistical data.
- Histograms are used to capture important information about the data in a concise representation [WS03]
- Selectivity estimation

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One-Dimensional Histograms

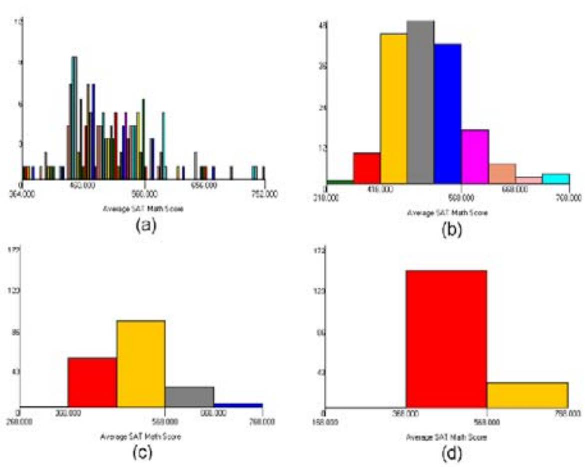

Figure 3.13: Equi-width histograms of a data set that containing the SAT math scores of students in some colleges with various bin sizes. These figures were captured from [NIS05].

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Selectivity Estimation for M-D Datasets

- 1-D histograms
  - Dimension independent assumption
  - Project data set to each dimension and construct a 1-D histogram upon each projection
  - For a given multi-dimensional range (*query*), the number of data items falling into this range (*selectivity* of the query) is estimated in this way:
    - Project the query on each dimension, estimate the selectivity of each one-dimensional query using the 1-D histograms
    - Multiply the selectivities from all one-dimensional queries to get the selectivity of the multi-dimensional query

Selectivity Estimation for M-D Datasets

- M-D histograms
  - A multi-dimensional histogram partitions the data space into buckets in the multi-dimensional space. In each bucket, the data distribution is often assumed to be uniform and recorded using simple statistic data.

Accuracy Comparison of 1-D and M-D approaches

- Assumption: All histograms are accurate
- Comparison: M-D ☺ 1-D ☹
- Reason: 1-D approach is based on attribute independent assumption, which is often false in M-D space
- Example:

  t.A = t.B for all tuples

  10% tuples have t.A = t.B = 0.5

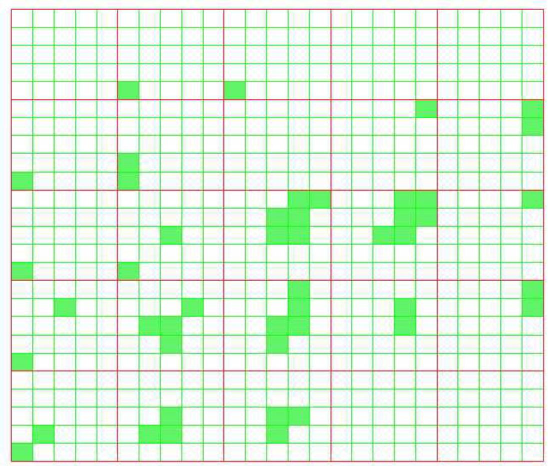
  Query "count tuples whose t.A = 0.5 & t.B = 0.5"

  - Answer of 1-D approach: 1% ☹
  - Answer of M-D approach: 10% ☺
- However, accuracy of M-D histograms degrades fast with increasing dimensionality!

Finite VS. Real Domains

- Finite domains:
  - Data distribution can be accurately expressed.
  - Number of distinct values in a bucket is often recorded so that frequency of each distinct value combination can be estimated.
- Real domains:
  - Infinite possible distinct values
  - Not many values will appear more than once.
  - Data distribution can hardly be accurately expressed.
  - Density of a bucket is often recorded and used.

M-D Histogram in MRV Application



A multi-dimensional histogram with equal sized bins visualized in Dimensional Stacking[WLT94].

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Approximation Operators

- Approximation - a simplification in which objects and relationships are represented by fewer objects and simpler relationships without explicit many to 1 mappings.
- Approximation operators include:
  - Proximity positioning operators
  - Wavelet operators
  - Other operators

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Proximity Positioning Operators

- Proximity positioning
  - Proximity positioning generates a topology preserving map of a collection that gives an overview of similarity among the objects within the collection. In the map, similar objects are positioned close to one another, and far from dissimilar ones [Bas01].
- Example proximity positioning operators:
  - Multi-Dimensional Scaling (MDS)
  - Principal Component Analysis (PCA)
  - Self Organizing Map (SOM)
  - Pathfinder Network Scaling (PNS)

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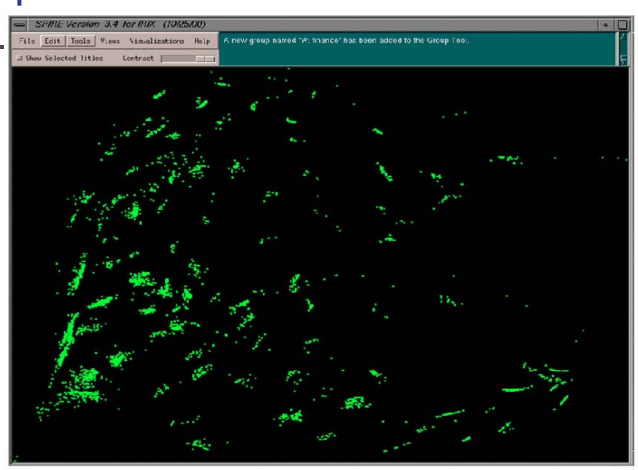
Proximity Positioning Operators in MRV Application



A document collection visualized in the SPIRE Galaxies visualization [NHT01]. This figure is used without authors' permission.

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Wavelets Operators

- Wavelets - filter matrices that accept a data stream with items, and generate items of approximations and items of details. The approximation is a coarse summary of the original data, and details contain the data loss during the decomposition [WB96].

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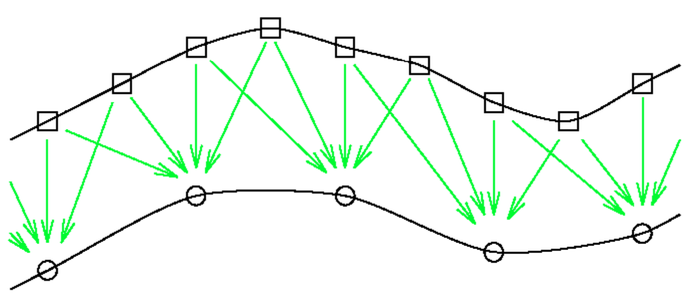
Wavelets Illustration



A fine data curve is downsized to a coarse one using wavelet decomposition [WB96]. This figure is used without authors' permission.

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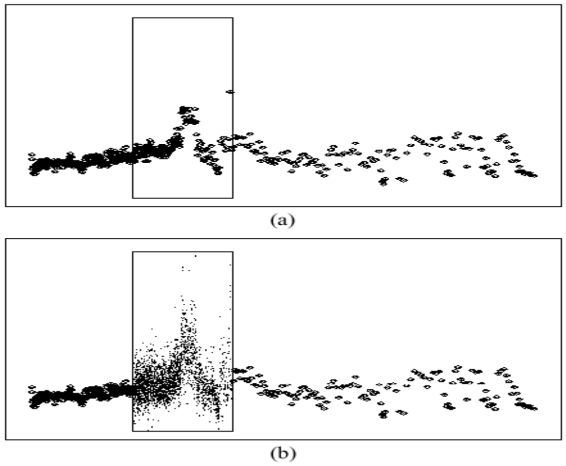
Wavelets in MRV Application



The wavelet brushing example [WB96]. (a) The brush data is defined. (b) Fine brushed data is painted over a coarse data background. This figure is used without authors' permission.

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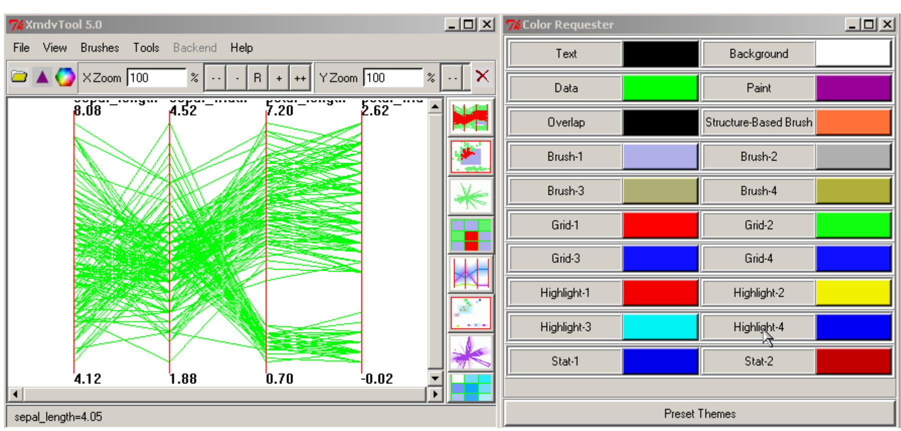
Generalization Operators

- Generalization - a simplification in which a set of similar objects is regarded as a generic object [SS77].



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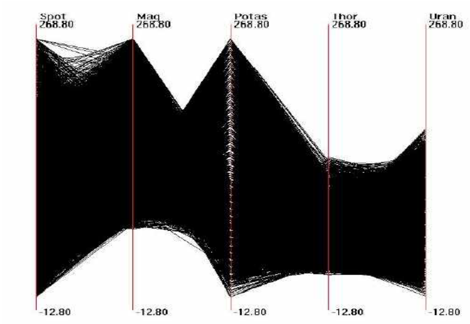
Generalization in MRV Application

Simplification Operands

- Data space (structure level)
  - Data item space
  - Dimension space
  - Topology space
- Visualization space (language level)
  - Visualization structure space
  - Visual encoding space
  - Screen space

Data Item Space

- Data items - individual objects contained in a data set



The clutter problem of data item space [YWR03b]. The Out5d data set (size: 16384 data items, 5 dimensions) visualized with parallel coordinates.

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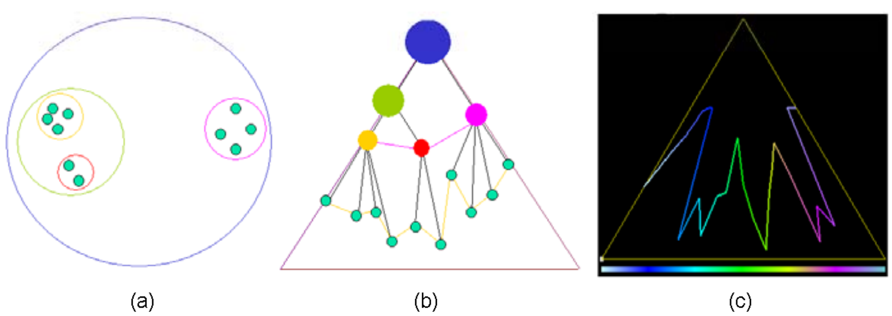
Data Item Space Simplification Example – IHD framework



(a) Clustering. (b) Hierarchy generated. (c) Approximation display [FWR99a, FWR99b, YWR03b]

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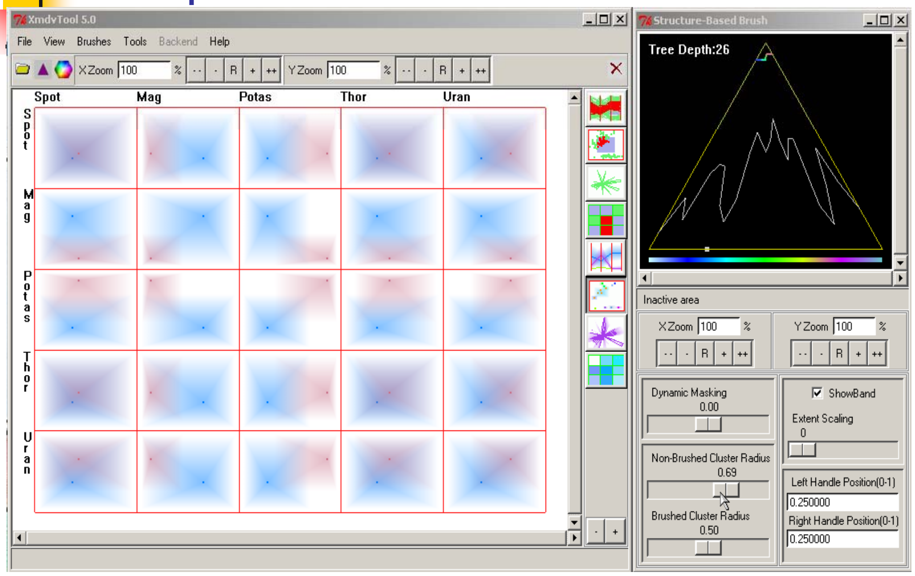
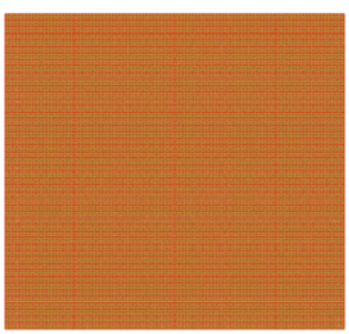
Data Item Space Simplification Example – IHD framework

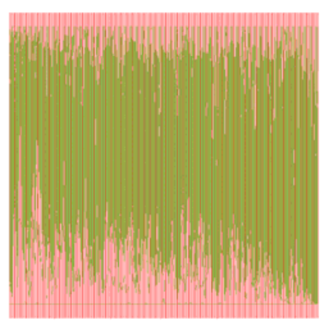


Dimension Space

- Dimensions - individual attributes of objects contained in a data set



46,225 plots



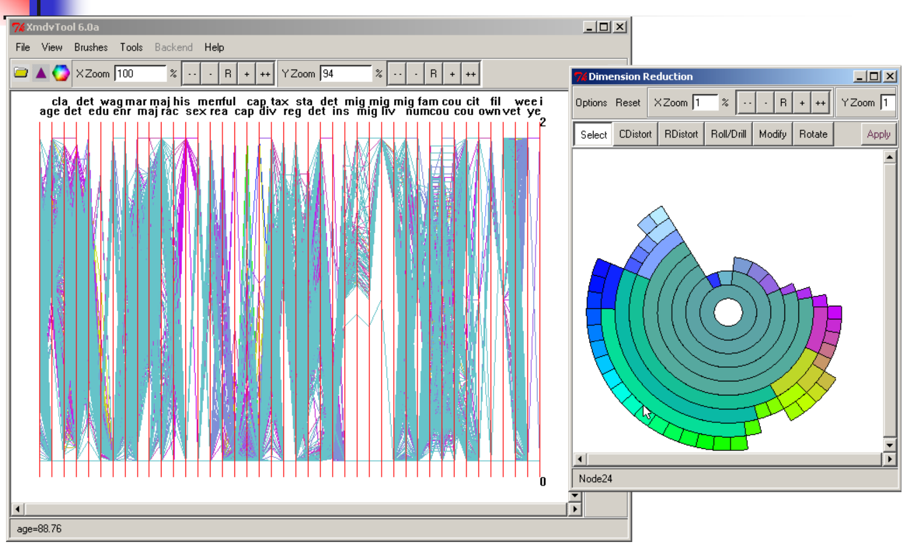
215 axes

The clutter problem of dimension space. The OHSUMED dataset (215 dimensions) visualized with a scatterplot matrix and parallel coordinates.

Dimension Space Simplification Example 1 – VHDR Framework

- Key ideas of Visual Hierarchical Dimension Reduction (VHDR) framework [YWRH03]:
  - Build a dimension hierarchy by clustering the dimensions to convey dimension relationships
  - Allow users to navigate and modify the dimension hierarchy
  - Allow users to select dimensions or dimension clusters to form subspaces of interests
- Simplification operator: clustering

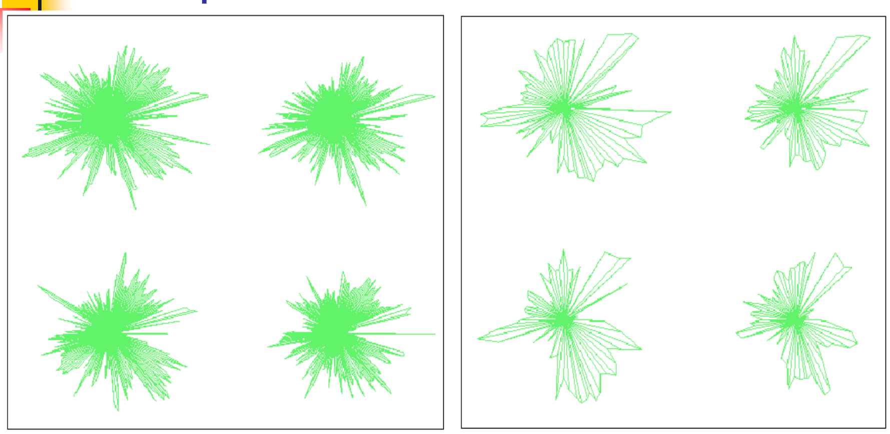
Dimension Space Simplification Example 1 – VHDR Framework



Dimension Space Simplification Example 2 – VHDF Framework

- Key ideas of Visual Hierarchical Dimension Filtering (VHDF) framework [YPWR03]:
  - Redundant dimensions can be removed
  - Unimportant dimensions can be removed
- Simplification operator: sampling and clustering

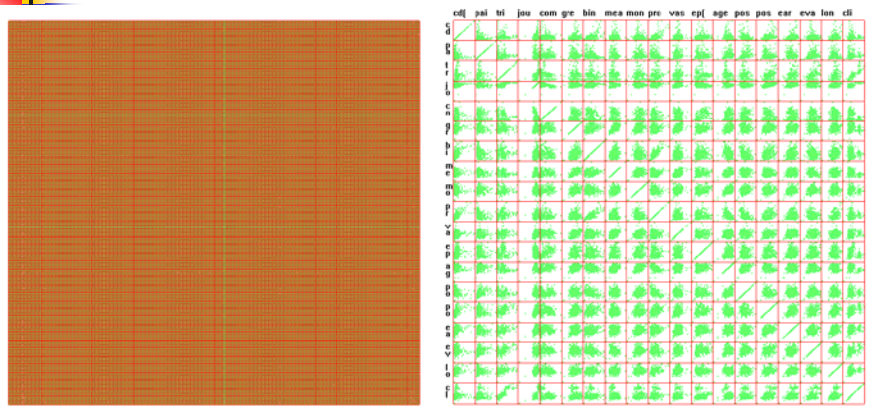
Dimension Space Simplification Example 2 – VHDF Framework



(a) (b)

Dimension filtering in star glyphs [YPWR03]. Four data items in the OHSUMED data set are shown. (a) Before filtering (b) After filtering.

Dimension Space Simplification Example 2 – VHDF Framework



(a) (b)

Dimension filtering in scattterplot matrices [YPWR03]. The OHSUMED data set is shown. (a) Before filtering (b) After filtering.

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Dimension Space Simplification Example 3 – VaR Displays

- Key ideas of Value and Relation (VaR) display [YPH+04]:
  - Convey dimension relationships using MDS
  - Convey data values using pixel-oriented techniques
  - Visualize dimension relationships and data values in the same display
- Simplification operator: MDS

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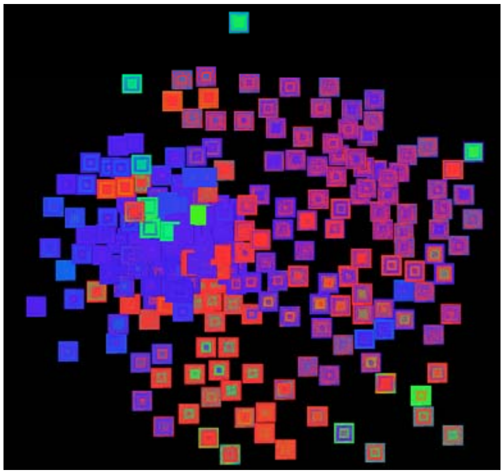
Dimension Space Simplification Example 3 – VaR Displays



SkyServer dataset: 361 dimensions, 50,000 data items

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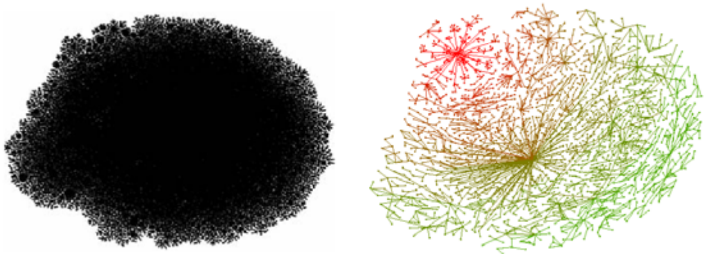
Topology Space

- Topology - geometric, spatial, temporal, or logical relationships among objects in a data set.



(a) (b)

A graph that contains 87,931 vertices and 87,930 edges [GKN04]. (a) The display is seriously cluttered. (b) The same graph displayed in lower levels of detail. This figure is used without authors' permission.
Simplification operator: hierarchical clustering

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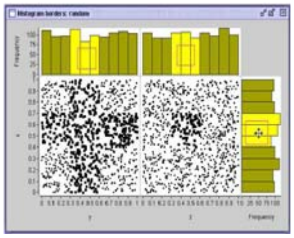
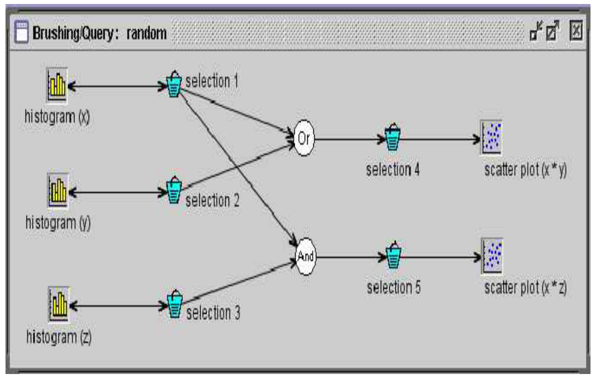
Visualization Structure Space

- Visualization structure - the organization of a visualization

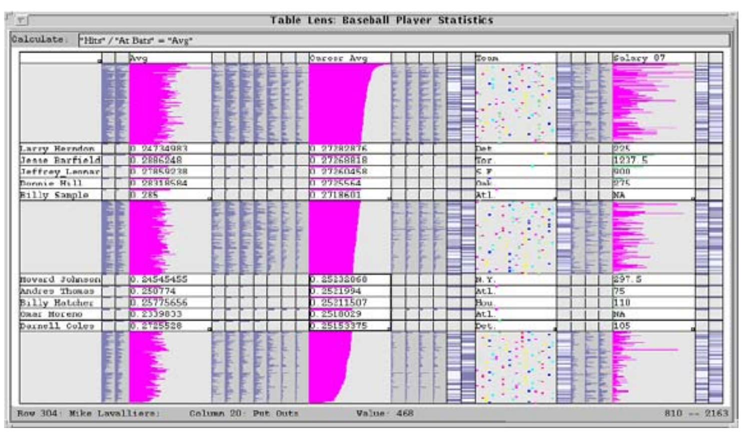




The Compound Brush [Che03]. Users can easily modify the brushing process by manipulating visual entities in the right window. This figure is used without authors' permission.
Simplification operator: generalization

Visual Encoding Space

- Visual encoding - the mappings between data and visual attributes

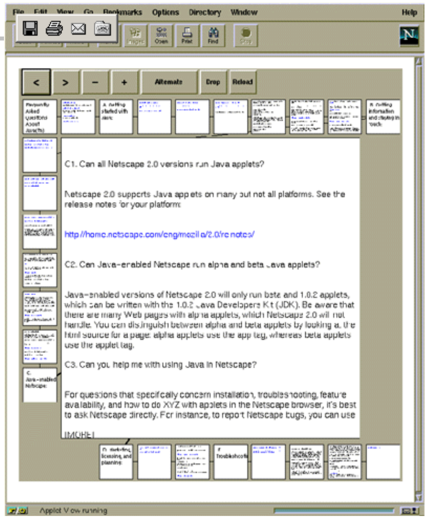


A basketball player statistics data set shown in the Table Lens [RC94]. This figure is used without authors' permission.

Screen Space

- Screen space - the pixels composing a display

The Zoom Browser displays context web pages as tiles around the focus page [Hol97]. Each tile contains a thumbnail or a summary of a context web page. This figure is used without authors' permission.



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Interactive Visualization

- Common interfaces of MRV systems:
  - Zoomable interface
  - Overview + detail interface
  - Focus + context interface
- Common interactions of MRV systems:
  - Zooming/panning
  - Selection
  - Distortion
  - Overlap reduction
  - Preview, dynamic simplification, and others

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Zoomable Interface and Zooming/Panning

- Zoomable interface - an interface in which objects are organized in space and scale and users directly interact with the information space mainly through panning and zooming [HBP02].
- Zooming in - the interaction that changes the current display from a view of a lower level of detail to a view of a higher level of detail.
- Zooming out - the interaction that changes the current display from a view of a higher level of detail to a view of a lower level of detail.
- Panning - the interaction that changes the current display from a subregion of a view to an adjacent sub-region of the same view. There can be overlaps between the two regions.

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Zoomable Interface and Zooming/Panning in MRV Application

Interactive map from www.mapquest.com

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Overview + Detail Interface and Selection

- Overview + detail interface - an interface composed of multiple windows. Some windows provide context and easy navigation (overview windows) for other windows (detail windows).
- Selection - the interaction that isolates a subset of entities on a display for further operations [Wil96].

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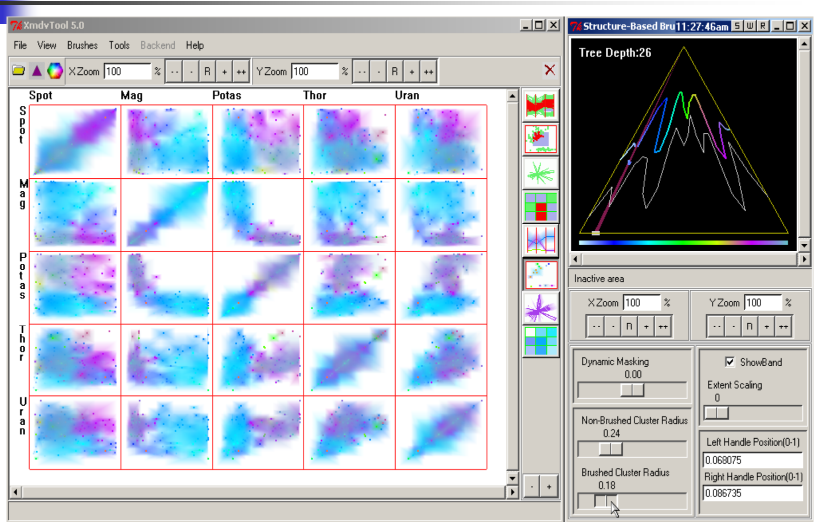
Overview + Detail Interface and Selection in MRV Application



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Focus + Context Interface and Distortion

- Focus + context interface - an interface where views of different levels of detail are mixed together in the same display.
- Distortion - an operation that increase the screen space allocated to some objects in the display while decreasing the screen space allocated to other objects.

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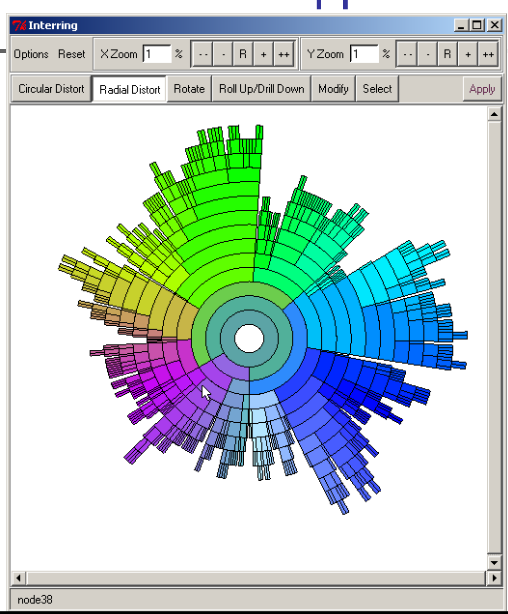
Focus + Context Interface and Distortion in MRV Application

InterRing [YWR02, YWRP03]



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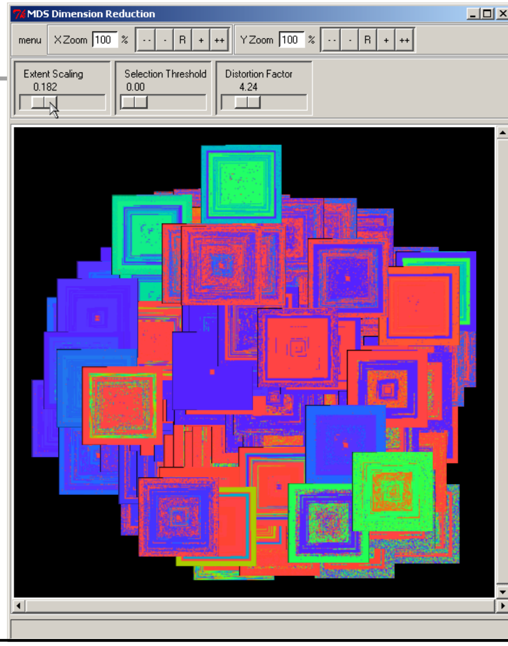
Overlap Reduction in MRV Application

- VaR display [YPH+04]
  - Extent Scaling
  - Dynamic Masking
  - Zooming and Panning
  - Showing Names
  - Layer Reordering
  - Manual Relocation
  - Automatic Shifting



Usability Inspection for MRV Systems

- Usability inspection answers questions:
  - Which simplification operator and operand to be chosen?
  - Which interface and interactions to be chosen?
  - Does a MRV system really solve the problems for which it is intended?
  - Which existing MRV system to be chosen?
- Popular usability inspection methods:
  - User testing
  - Heuristic evaluation

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Summary

A general framework for MRV systems

- View simulation
  - Simplification operators
    - Sampling, aggregation, approximation, and generalization
  - Simplification operands
    - Data space and visualization space
- Interactive visualization
  - MRV interfaces
    - Zoomable, overview + detail, and focus + context interfaces
  - MRV interactions
    - Zooming, panning, selection, distortion, overlap reduction, ...