Multiscale Geometry and Analysis of High Dimensions
25-30th October 2004, UCLA, USA

Bielefeld
The Neuroinformatics Group

# Multiscale Auditory Displays

## Interacting with the complexity level in Model-based Sonification

Thomas Hermann
Neuroinformatics Group, Faculty of Technology
Bielefeld University, Germany

## Outline

- Sonification – An Overview
- **Model-based Sonification**
  - Framework
  - Discussion
- **Sonification Models**
  - Data Sonograms
  - Particle Trajectory Sonification Model
  - Discussion
- **Growing Neural Gas Sonification**
  - GNG-Networks, Adaptation, Qualitative Behavior
  - Extension to Growth-Process Monitoring
- **Data Crystallization Sonification**
- Conclusion



## Why sound? - Motivation

- Humans use several perceptual senses!
  **So why rely on vision alone for Datamining?**
- Humans have **excellent listening skills**!
  - High-developed Pattern Recognition Capabilities
  - High Spectral and Temporal/Rhythmical Resolution
  - Parallel Processing of several information streams
  - Multiple information layers: e.g. speech: symbol, prosody
  - Backgrounding, sound is able to draw/guide Attention
  - Source Separation, Operation in noisy contexts
  - Provides qualitative Information (opposed to Quantity)
  - Auditory Gestalt Formation ⇔ Auditory Learning

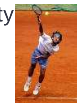


## Applications for Sonification

- Extension/Replacement for visual display

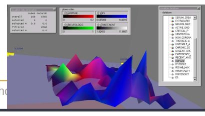
- Multi-modal User Interfaces

- Coordination of actions and human activity



- **Process Monitoring**

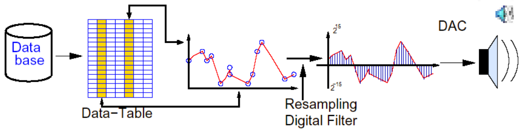
- **Exploratory Data Analysis**
  → to discover the unexpected





## Sonification Techniques

- **Audification**: (Examples: EEG: Helicopter-Flights: )

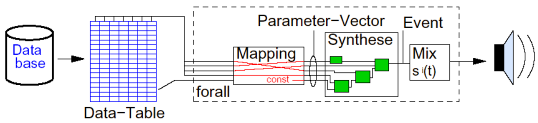



- Limited to large datasets
- Time ordering required
- Variations in data required



## Sonification Techniques (cont.)

- **Parameter Mapping**: (Examples: EEG: Traffic: )



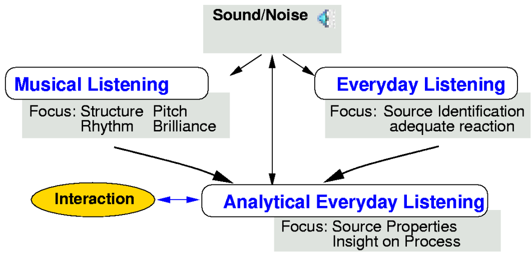

- Limited number of acoustic parameters
- Different saliency of parameters, and nonlinearity
- Curse of complex specification
- Missing connection of modalities
- Every Mapping is a Unique design

# How do we hear?

- Real-world: Sound is “by-product” of physical (dynamic) system
- Listening: is optimized to perform „inverse mapping“
- Data-world: Data are static feature vectors
- Example: Describe what you hear!



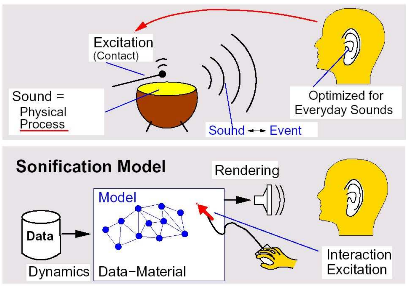
# Listening Modes





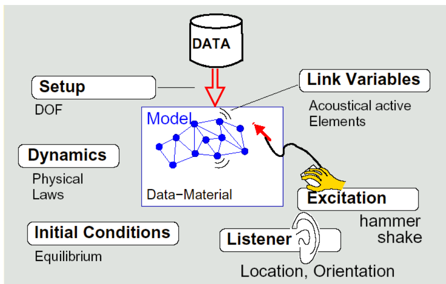

# Model-based Sonification

- Model-coupling between data and media






# Sonification Model Construction





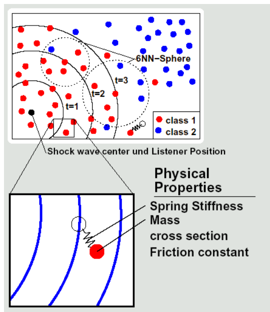

# Sonification Models

- Data Sonograms
- Particle Trajectory Sonification Model
- Principal Curve Sonification
- McMC Sonification (with M. Hansen)
- Data Solids
- Local Heat Exploration Model
- Growing Neural Gas Sonification
- Data Crystallization Sonification

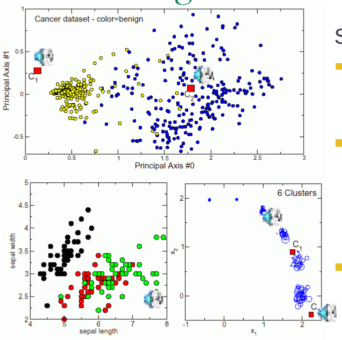


# Data Sonograms

- **Setup:** Point Masses in Data Space
- **Dynamics:** Newton’s laws
  - Spring Forces
  - Wave Propagation
- **Excitation:** Shock Wave (pressure wave)
- **Link-Variables:** Point mass elongations
- **Listener:** binaural
  - Orientation: PCA#1



## Data Sonogram Examples




Sound Examples:

- Breast Cancer Diagnosis
  - N = 700, d = 10
  - ⇨ Distances in hd spaces
- Iris Dataset
  - N = 150, d = 5, 3 sorts of plants
  - ⇨ Class separation
- Clustered Data in $R^3$
  - ⇨ Spatial relations



## Particle Trajectory Sonification

Model for Cluster Analysis

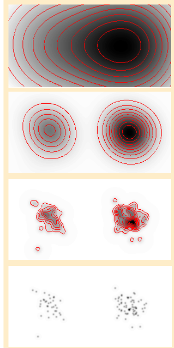
- **Setup:** Particles in Data Potential

$$V(\mathbf{x}) = \sum_{\alpha=1}^{M} \phi(\|\mathbf{x} - \mathbf{x}_i\|) \quad , \quad \phi(r) = -N \exp\left(-\frac{r^2}{2\sigma^2}\right)$$

- **Dynamics:** Newton's Law + damping

$$m\ddot{\mathbf{x}}(t) = -\nabla_x V(\mathbf{x}) - \gamma \dot{\mathbf{x}}(t)$$

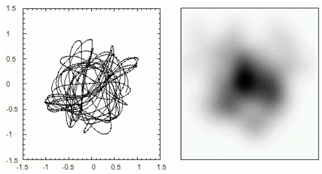
- **Excitation:**
  - Particle Injection
  - Energy Injection (shake, hammer)
- **Link-Variable:** kinetic particle energy





## Particle Sonifications (cont.)

- Typical Particle behavior:
- Parameters:
  - Mass
  - Bandwidth σ
  - Friction constant



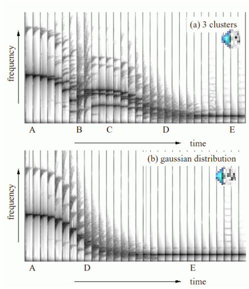
- Represents V in multiple resolutions in time
  chaotic → timbral → pure harmonic → sinusoid



## Particle Trajectory Sonification

Holistic multiscale encoding of properties of *V(x)*

- Single particles
  → not very informative
- **Particle Ensembles** summarize properties
  - Example: 1 or 3 clusters
- **σ-sweeps:**
  → Multiscale Analysis
  → „Auditory Gestalt"






## MBS-Discussion

+ Separation of Design/Use
+ Generality
+ Model facilitates Interpretation
+ Built-in Interaction Concepts
+ Fewer & more intuitive Control Parameters
+ Supports Task-Oriented Design

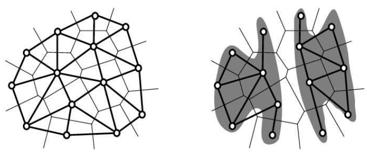
↳ **New Perspective on Acoustic Data Representation**

- High computational complexity



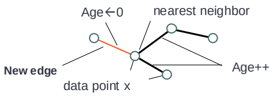
## Growing Neural Gas Networks

- Conceptually between Vector Quantization and SOM
- **Local Method**: Neuron Weight Vectors as Prototypes
- Flexible Topology (compared to SOM or Principal Manifolds)



a) Delaunay triangulation    b) induced Delaunay triangulation

# GNG Algorithm

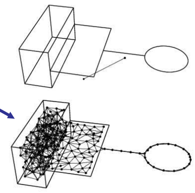


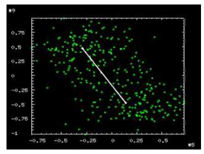

1. Draw a data point **x** from the underlying distribution.
2. Find the nearest and second nearest neurons $i_1$, $i_2$.
3. Increment the age of all edges emanating from neuron $i_1$.
4. Update $R_{i1} \leftarrow R_{i1} + k\|\mathbf{w}_{i1} - \mathbf{x}\|$
5. Update neuron $i_1$ and its topological neighbors $n$ by
   $$\mathrm{w}_{i1} = \varepsilon_b(\mathrm{x} - \mathrm{w}_{i1}), \quad \mathrm{w}_n = \varepsilon_n(\mathrm{x} - \mathrm{w}_n)$$
7. Create edge j between neuron $i_1$ and $i_2$, if it does not already exist. Set its age $A_j = 0$.
8. Remove old edges ($A_i > a_{max}$). Remove ´edgeless´ neurons.
9. Every $L$ steps:
   1. **Insert new neuron $q$ between the neuron $q_1$ = arg max$_i$ $R_i$ and its topological neighbor neuron $q_2$ with the largest error. Handle edges.**
   2. **Update** $R_{q1} \leftarrow \alpha R_{q1}$ , $R_{q2} \leftarrow \alpha R_{q2}$ and set $R_q = R_{q1}$
10. Decrease errors $R_j = \alpha R_i$ with $\alpha < 1$.
11. goto 1 (until a stopping criterion is fulfilled).

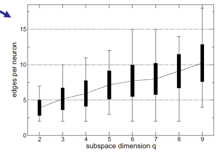


# GNG Properties

- Topology Preserving
- Incremental Memory
- Segmentation of Clusters
- Map Magnification (Fovea Effect)
- Connectivity ⇔ ID
- Pure Online Learning



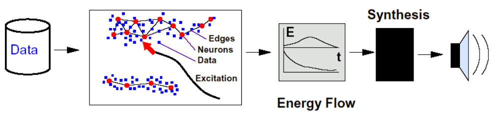







# Sonification of GNGs

Model for Exploration/Comparison of local intrinsic data dimensionality




- **Setup:** GNG-computed neuron objects as acoustic entities
- **Dynamics:** Atomic acoustics & energy flow
- **Excitation:** all sorts, e.g. hammering, shaking
- **Listener:** not localized w.r.t. the model



# GNG Neuron Sonification

- Allows Task-Oriented Design
- Simplest choice: spring stiffness ← #edges
- Implicit dimensionality display
  - Single Neuron sound conveys **local dimensionality properties** of the network
- Integer #edges → harmonics, periodic waveforms

**Excitations:**

- **Browsing:** Excite single Neurons
- **Growth Process:** Representation at changing complexity

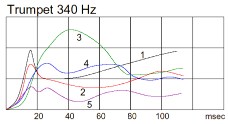


# Acoustic Energy Propagation

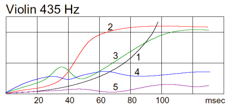
$$\frac{dE_i}{dt} = -gE(t) - \sum_{j \in I_N(i)} q(E_i(t) - E_j(t))$$

- Energy spreads into **topological** neighborhood
- Dynamics induces **Timbre evolution** (typical in real instruments)
- High Sensitivity on **local characteristics**
- Temporal evolution → Multiscale analysis

Trumpet 340 Hz




Violin 435 Hz

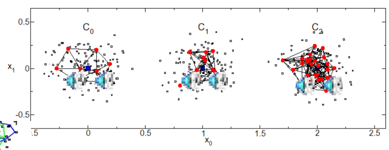


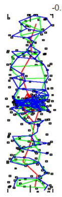



# GNGS-Probing/Examples

- Gaussian Distributions of Rank d →

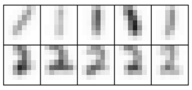
1
2
3
4
5
6
7
8

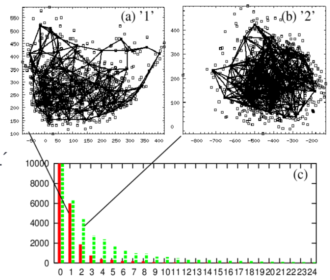


- Mixture of 2d/5d distributions
  - Energy Loss Series:
    0.99(edge, center) 0.95(center) 0.90(edge)
  - Energy Flow Series
    0.01(e) 0.1(e) 0.2(e) 0.5(e) 0.5(c)

# GNGS-Probing/Examples (cont.)





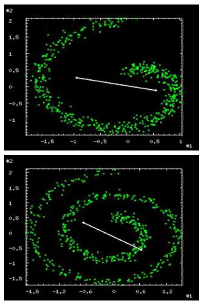

- MNIST digits
- ´2´ more complex than ´1´
- GNGS Examples

1:

2:



# GNG - Growth Process Sonification



- Noisy Spiral in $R^2$
  → reconfiguration of topology
- **Multiscale Analysis of Data**
  - Detect Overfitting
  - Evaluate stability of structure
  - Find adequate model complexity
- For comparison:
  Growth in a 5D Gaussian:



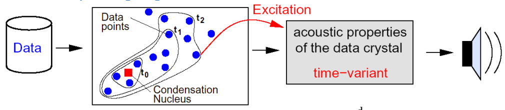
# Sonification as Multiscale Display

- **Browsing:**
  - Sound Evolution evolves from local info → global summary
  - Listening is particularly suited to follow changes
- **Growth Process:**
  - Model-Complexity scales with network size
  - Model evolves from under- to overfitting
- **Interaction:**
  - Analogous (e.g. squeezable) interfaces allow intuitive control of scale/resolution parameters.



# Data Crystallization Sonification

Model for exploring high-dimensional data




- **Setup:** Data atoms at vector positons $\mathbf{x} \in R^d$
- **Dynamics:** Data point inclusion into crystal set according to a growth inclusion law. E.g.distance dependent inclusion using linear mapping **t = map(||x-$x_c$||, [0, max$_i$ ||$x_i$-$x_c$||], [0,T])**
- **Initial State:** Empty Crystal Set
- **Interaction:** Trigger condensation nucleus in 2d-scatter plot
- **Listener:** non-localized w.r.t. model setup → monaural sound



# Data Crystal Acoustic Properties

- Growth changes Modes (Timbre)

$$\mathbf{C}_{xx}(t) = \frac{1}{|I_c(t)|} \sum_{\mathbf{x} \in I_c(t)} (\mathbf{x} - \bar{\mathbf{x}}(t)) \; (\mathbf{x} - \bar{\mathbf{x}}(t))^T$$

- Data Inclusion is exothermic process

$$\frac{dE}{dt} = -\gamma E + \sum_i g_i \delta(t - t_i)$$

- Modal Synthesis for Sound Computation

$$s(t) = \sum_i^d a_i(t) E(t) \sin(\omega_i t + \phi_i)$$

Harmonics

$\omega_0$=fkt(Size)

- Timbre Vector determined by Spectrum of $C_{xx}$

$$a_i(t) = \frac{\lambda_i(t)}{\sum_i \lambda_i(t)}^p$$

→ Timbre Evolution determined by Growth Process

→ Matches Human Listening Skills



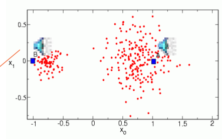
# DCS - Examples

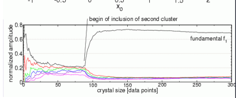
Gaussian Cluster

- DCS Center Tail edge

Mixture of 2 Gaussians

- Incr. E decay:
- Incr. Time:



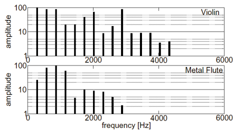


Mixture of 2d/4d/8d-cluster chain

- Starting in 2d 4d 8d cluster

## Crystallization Son. - Discussion

- Timbre changes with $C_{xx}$ over Time




- Resolution/Scope: From Local to Global
  → Multiscale Structure Display
- Transient Structure → Timbre Gestalt
- Generic Approach (principled…)
  - Intuitive control parameters
- Open for task-specific optimizations



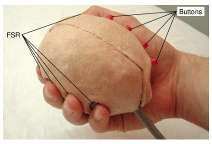
## Controlling the Complexity Level

- Complexity as „scale of resolution“ implementable in a Sonification Model
- Interaction is possible via
  - Control Parameters (e.g. Squeezing force)
  - Growth Processes
- Proposition: Interactively adjust complexity in a closed human-computer interaction loop.



## Ongoing research

- Multi-modal interfaces to high-dim. Data




- Tangible Computing with Sonification
- Application to challenging domains (EEG, etc.)



## Conclusion

- New Framework **Model-Based Sonification**
- Many **Sonification models** give examples
  - Physical motivated control parameters
  - Models ground the semantics of sound
  - Models offer integrated interaction concepts
  - **Generic** approach → Learnability
- **Neural Networks** provide suitable task-oriented mediating **representations** for **interaction and navigation**



## The End

Thank you for your interest!

**Questions? Comments?**