Spatial Aggegation

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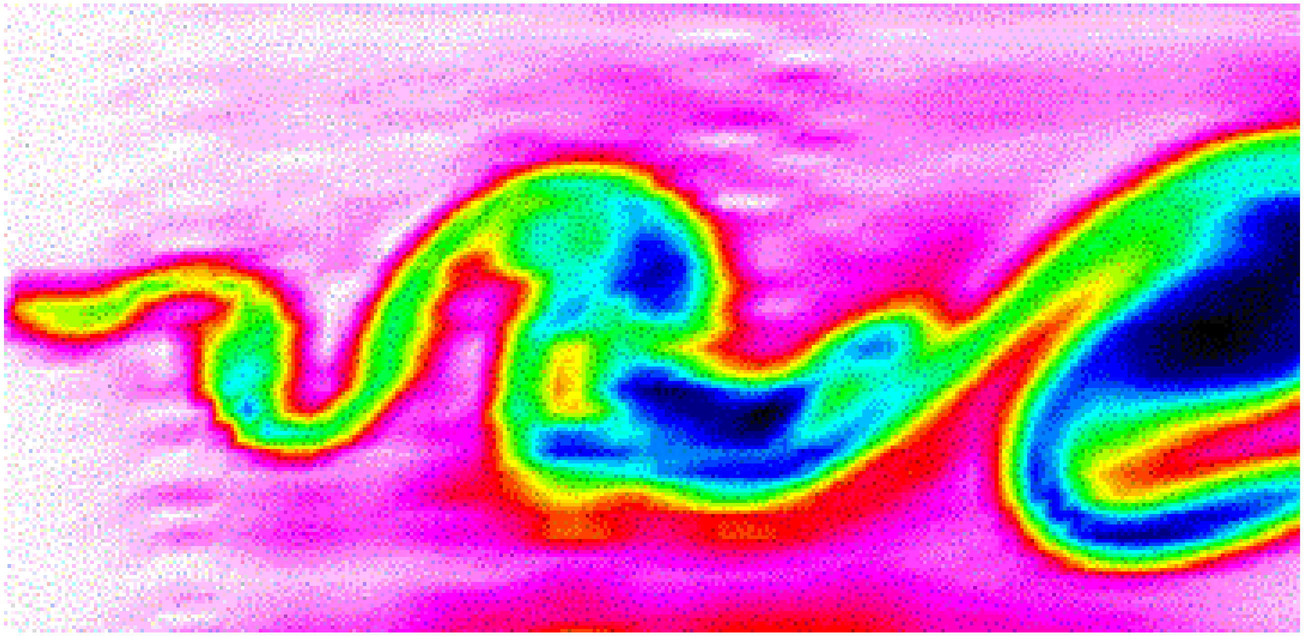
Physical Fields are Ubiquitous

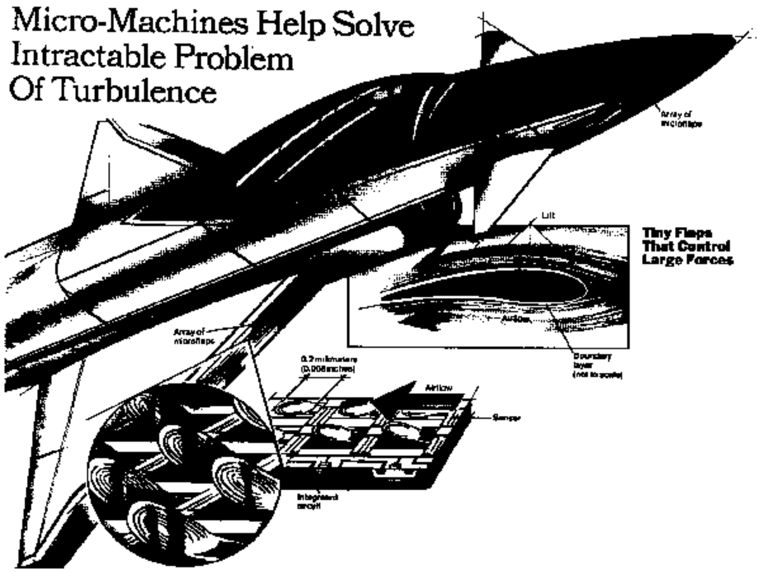
- Temperature, sound, fluid, …
- Practical applications:
  - Smart environments
    - E.g. Buildings, life support systems, transportation grids
  - Space science data gathering
    - E.g. Constellation of space probes
  - Weather prediction
  - Intelligent structures & materials
    - E.g. MEMS active surfaces

An Example of Physical Fields



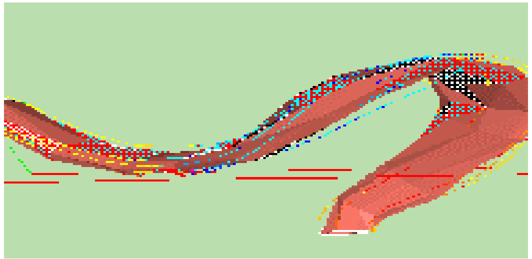
A fluid field showing high density regions and large vortex structures

Reducing air drag requires interpreting non-local structures in fluids

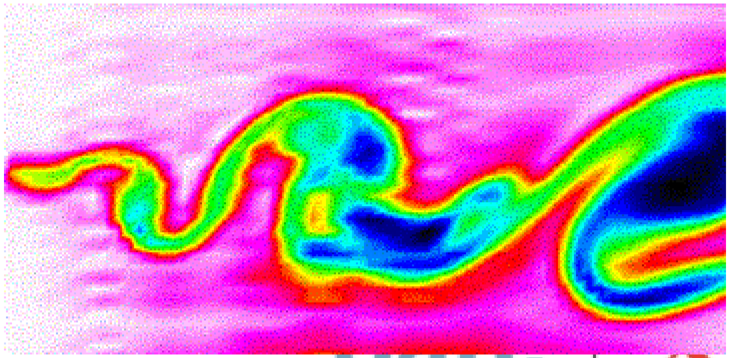


Distributed array of micro flaps interact with air flows to reduce air drag

- C.M. Ho, UCLA



- Control requires global models
- Spatial Aggregation computes high-level structural models of vortices in fluids (Yip, MIT)



Characteristics of Physical Fields

- Spatially distributed
- Continuous and data rich
- Multiple spatio-temporal scales
- Large D.O.F. and often nonlinear

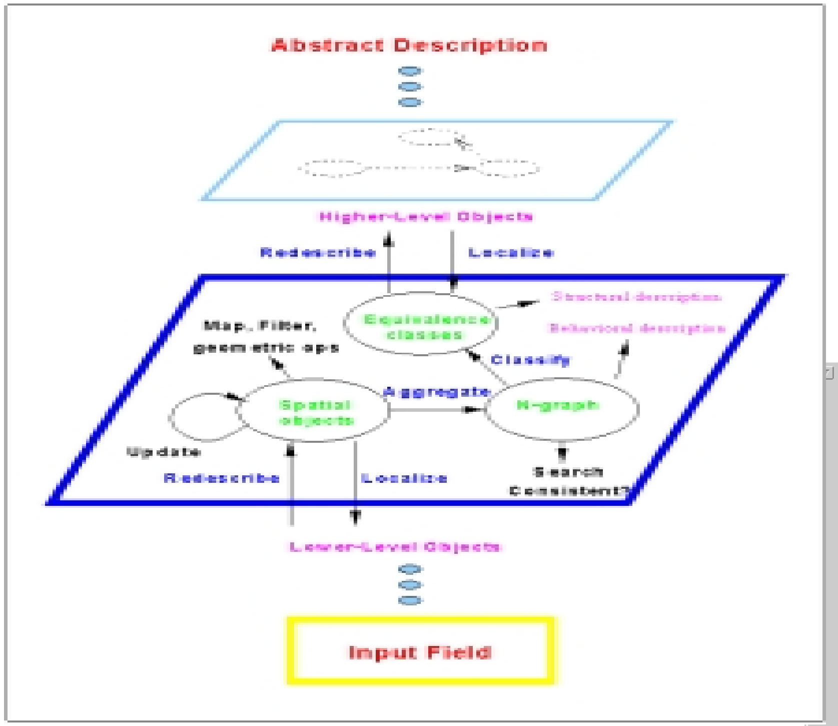
Scientists often describe a physical phenomenon in terms of spatio-temporally coherent **“objects”!**

- E.g. stability region, vortex bundle, pressure trough

The idea dates back to the beginning of last century

- Poincare’s geometric theory of dynamical systems

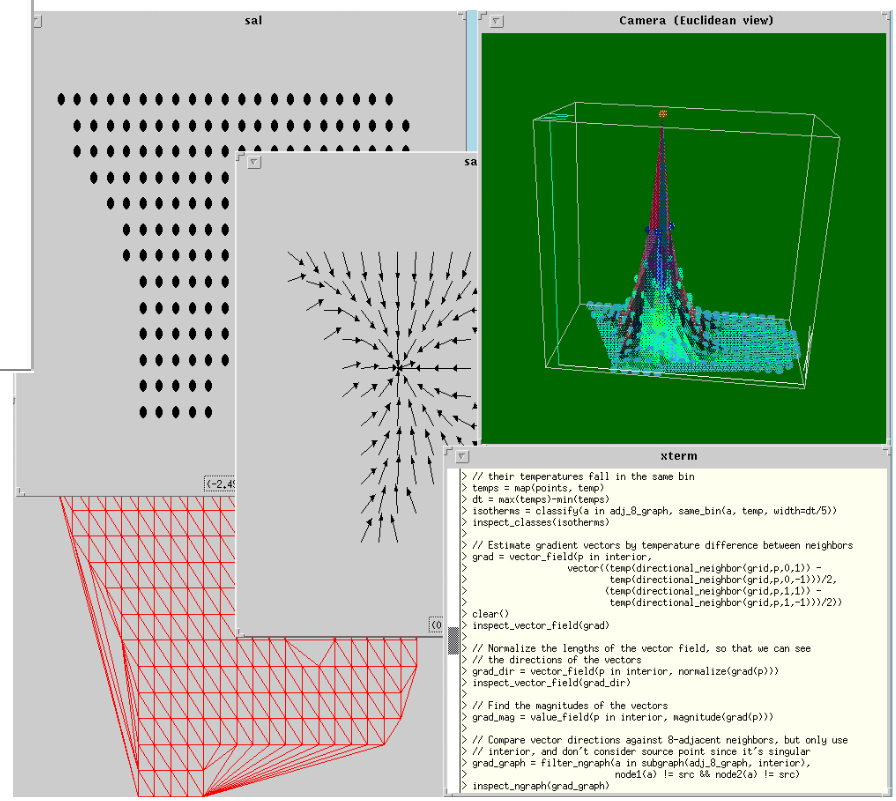
Tools for mining distributed data



SAL software tool

Spatial Aggregation

- Recursively aggregate local data to high-level descriptions
- Distribute global objectives to local actions

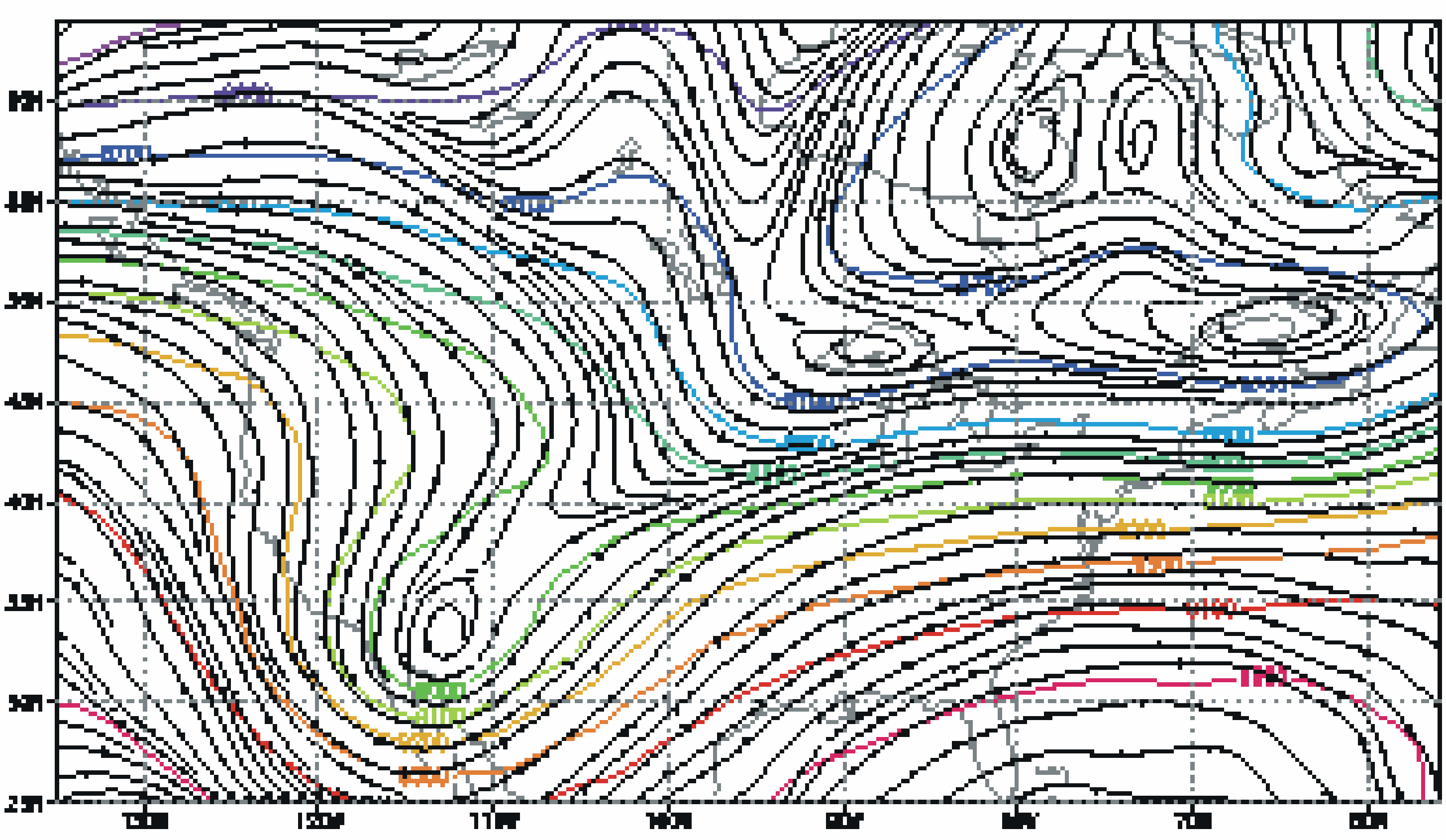


Applications to

- Weather analysis, pattern classification, control optimization.

Joint work with C. Bailey-Kellogg and K. Yip

Weather data: an example of spatio-temporal fields

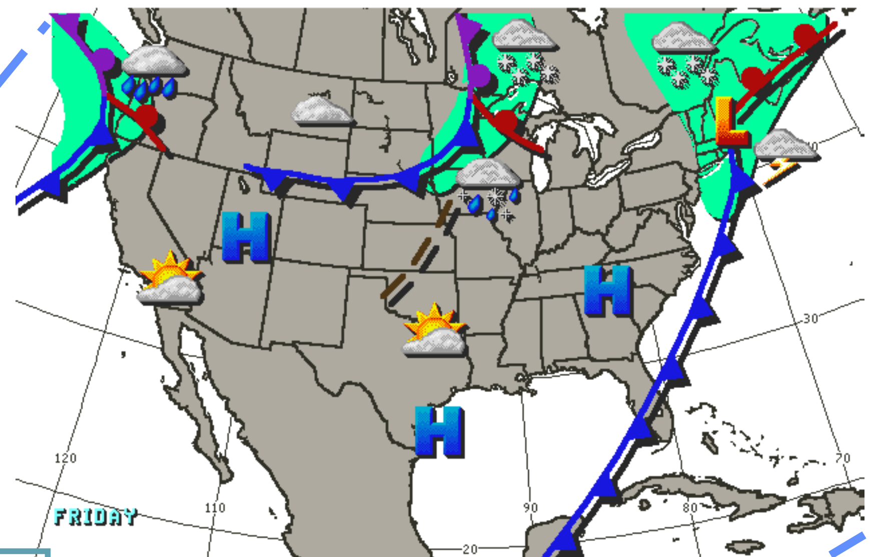


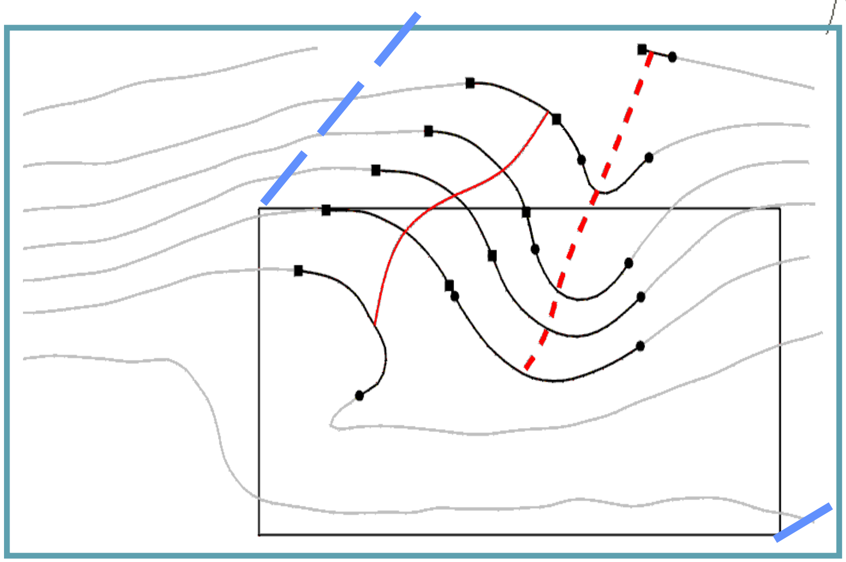
Pressure, temperature, wind vectors, …

Joint work with X. Huang

Interpret weather date sets

- **Bottom-up**: aggregate structures from data hierarchically
- **Feedback**: correlate multiple data sets to improve detection accuracy (global → local)



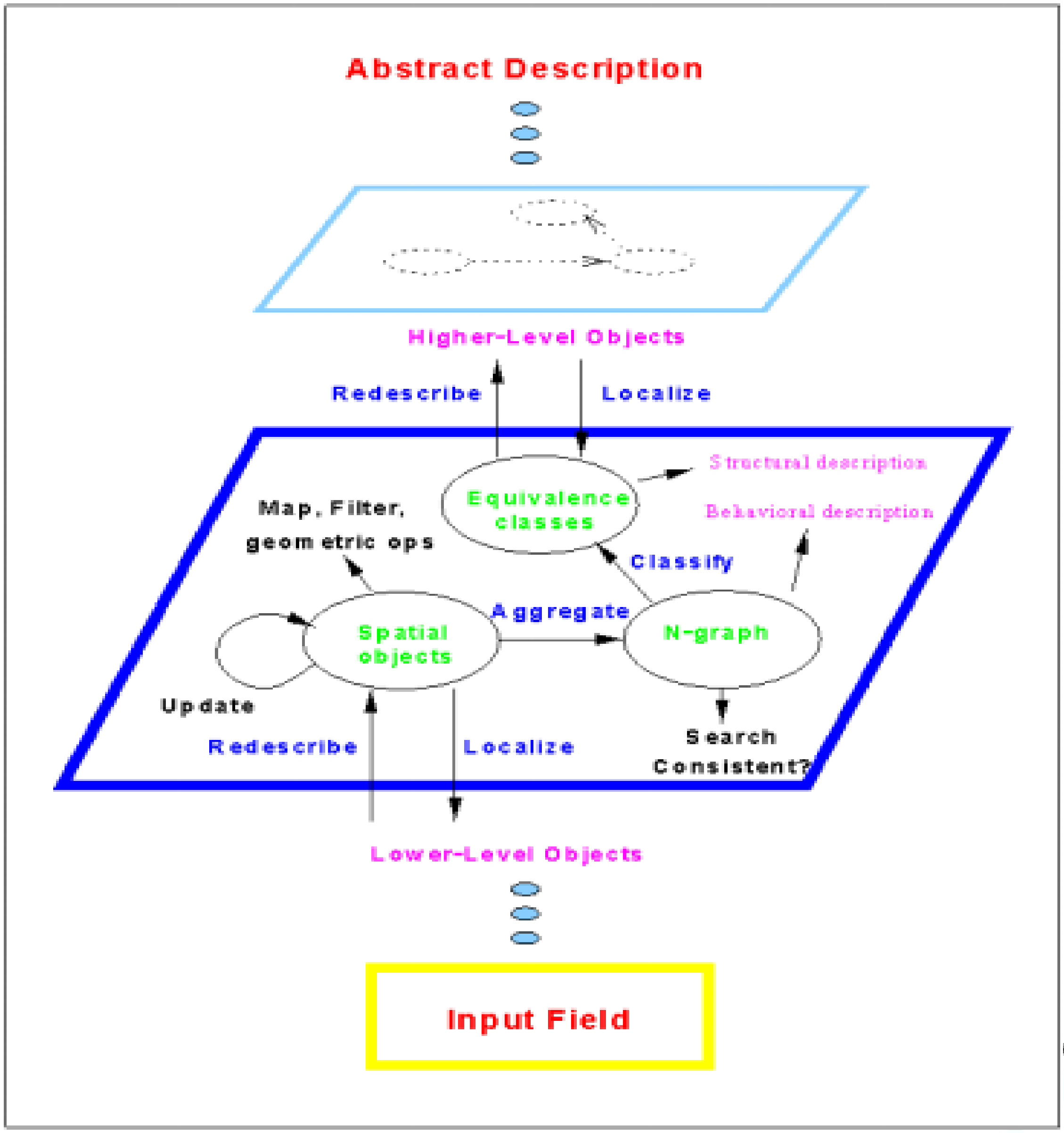


Result of automatic detection of pressure troughs

Overview of Spatial Aggregation (SA)

- **Input**: data-massive, numerical field
  - E.g. weather maps, seismic signatures, numerical simulation data
- **Output**: high-level description of structure, behavior, and control action
  - E.g. stability regions and bifurcation diagrams for dynamical systems, C-space free region diagrams for mechanical mechanisms, synthesized control reference trajectories
- **Task domains**
  - Sensor data interpretation; Control
- **Central computational problem**
  - Uncover structures of physical fields as communicable knowledge

Spatial Aggregation



Examples of Spatial Aggregation

- **KAM**: analyzing nonlinear dynamical systems (Yip)
- **MAPS**: synthesizing control laws (Zhao)
- **HIPAIR**: performing kinematic analysis of mechanisms (Joskowicz & Sacks)
- Mining data from **fluid dynamics** simulation (Silva & Zabusky; Yip)

Basic Elements of Spatial Aggregation

- Field ontology
  - How to describe the problem
- Neighborhood graphs and generic operators
  - How to decompose the problem and formulate problem-solving steps
- Multi-layers of spatial aggregates/ transformation
  - How to actually solve the problem

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Field Ontology

- A field is a mapping from one continuous space to another: $R^m \to R^n$
  - A grey-level image: $R^2 \to R^1$
  - Temperature field of the room: $R^3 \to R^1$
  - Wind velocity field in the air: $R^3 \to R^3$
- Metric on a field $\to$Topology$\to$Continuity
- A field is analogue: pointwise, numerical, information-rich

Elements of Field Ontological Abstraction

- Spatial objects
  - Geometric description
  - Feature description
    - E.g. temprature, pressure, velocity
- Constitutive laws
  - E.g. Fourier's law, Ohm's law, Hooke's law
- Spatial neighborhood structures
  - E.g. MST, Delaunay graph

Multi-Layer Transformation of N-Graphs

- A small set of operators construct and transform spatial aggregates
- Identical set of operators at each layer, parameterized by task and domain specific metric and relations
  - *Aggregate* forms a neighborhood graph explicitly encoding adjacencies
  - *Classify* forms equivalence classes of similar neighboring objects
  - *Redescribe* maps equivalence classes to higher-level objects

Spatial Aggregation Language (SAL)

- Support rapid prototyping of problem solvers for imagistic reasoning tasks
- Provide data types and operators
- Modular construction of transformations, organized by parameterized N-graph constructures

SAL source code is freely available at
http://www.parc.xerox.com/zhao/sal.html

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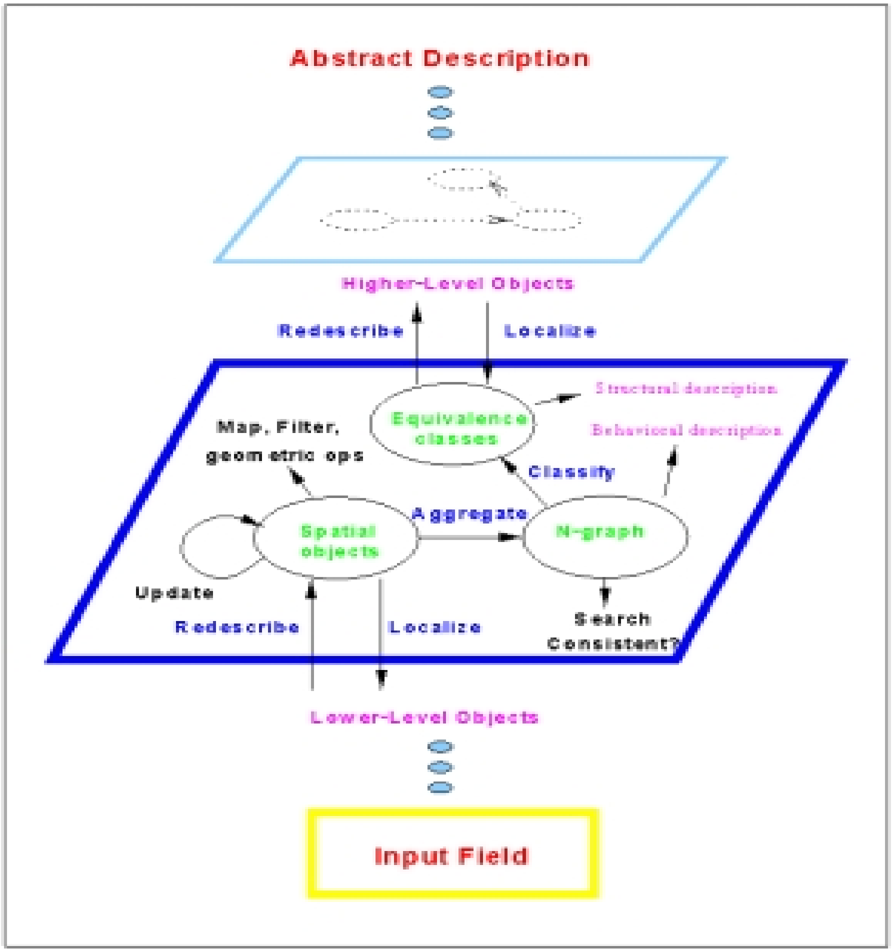
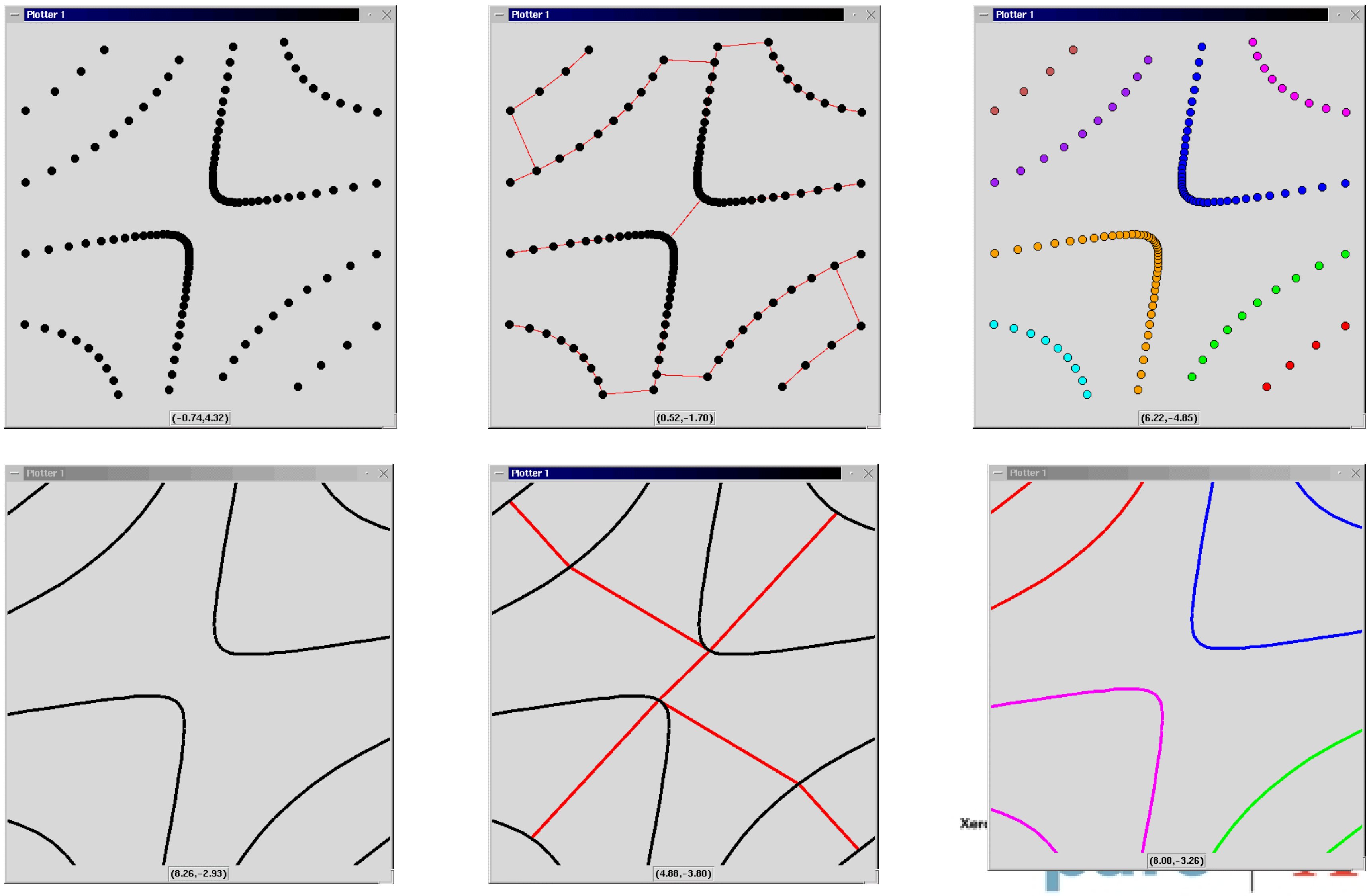
Programming in SAL

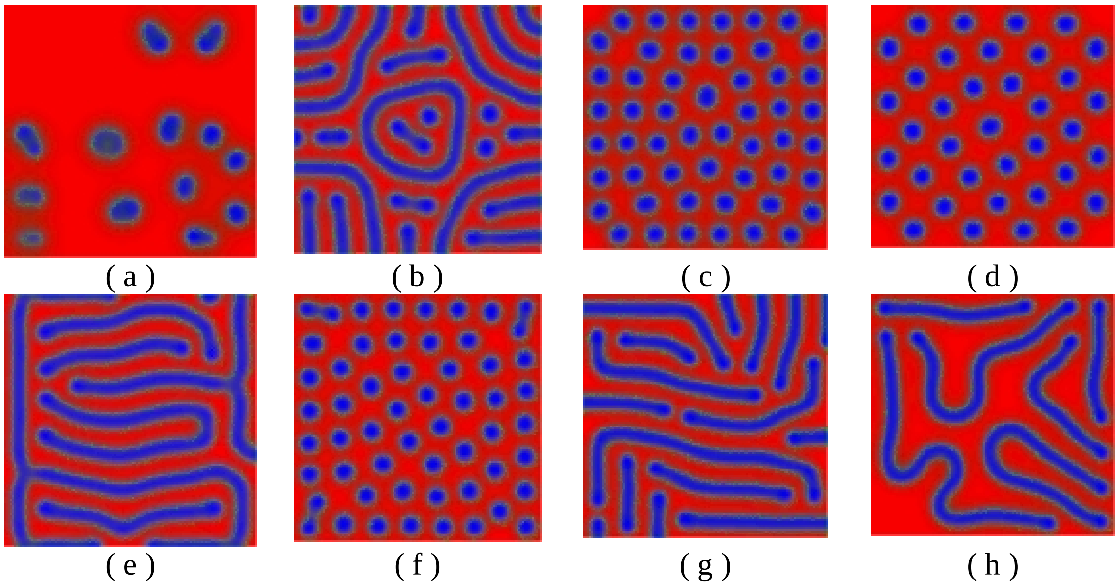


- Identify adjacency and equivalence relations
  - Continuity, spatio-temporal scales
- Determine abstraction levels
  - Substructure/structure relation
- Identify abstraction pre- and post-conditions

Trajector Bundling: an example



Automatic classification of time-varying diffusion-reaction patterns



- Useful models in biology, chemical reaction, and population dynamics.
- Automatic classification accounts for 83% of human expert interpretation (Pearson, *Science*, 1993)

Classification result:

- Cluster 1: History (h)
- Cluster 2: Histories (e) and (g)
- Cluster 3: History (b)
- Cluster 4: Histories (c), (d) and (f)
- Cluster 5: History (a)

Joint work with Ivan Ordonez

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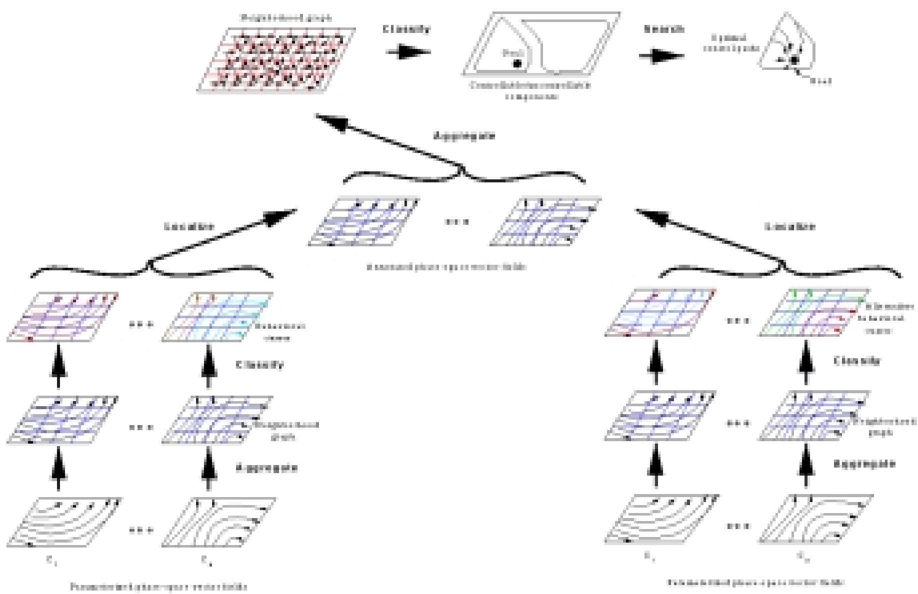
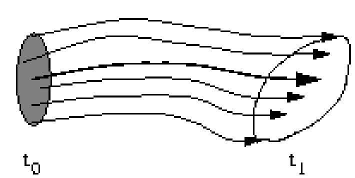
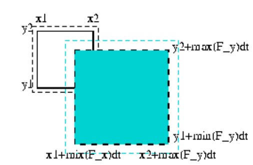
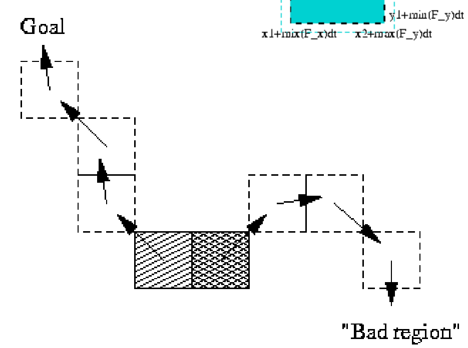
Controller Synthesis and Verification for Nonlinear Systems Using Phase-Space Geometric Models:
The Maglev Experience



•Geometric models of behaviors
•Hierarchical refinement
•Symbolic graph methods



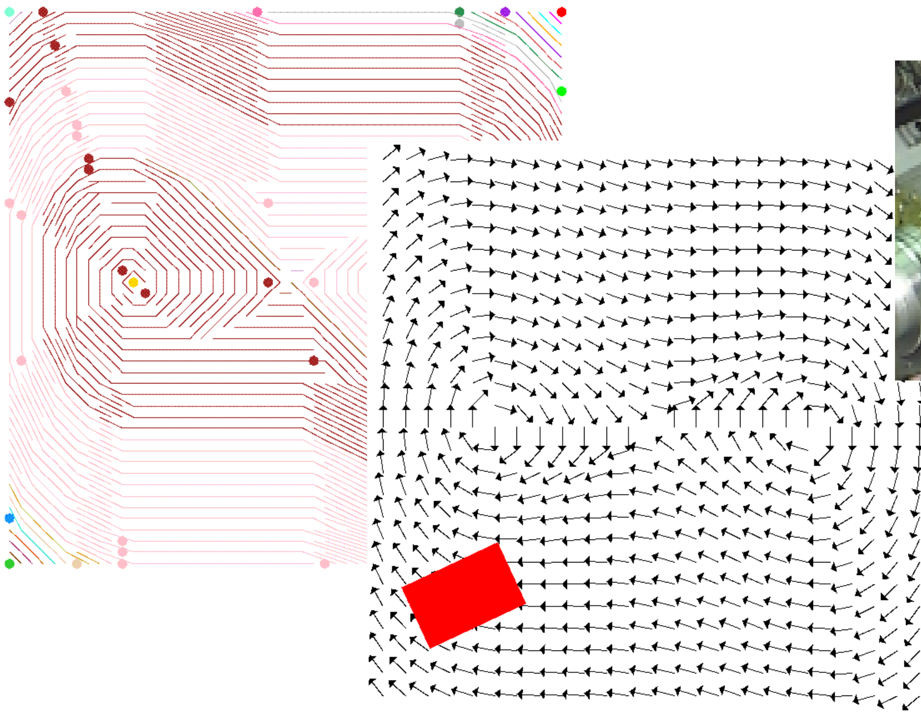


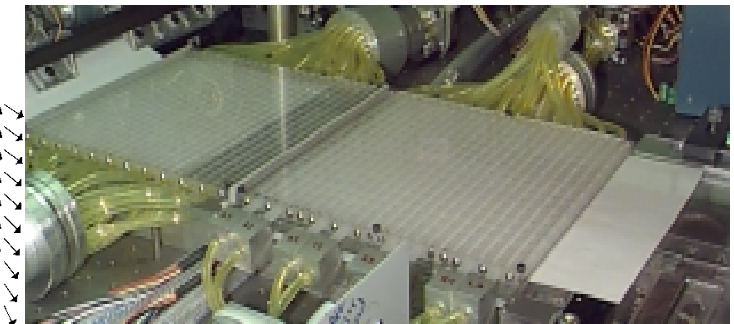


Behavioral programming and verification

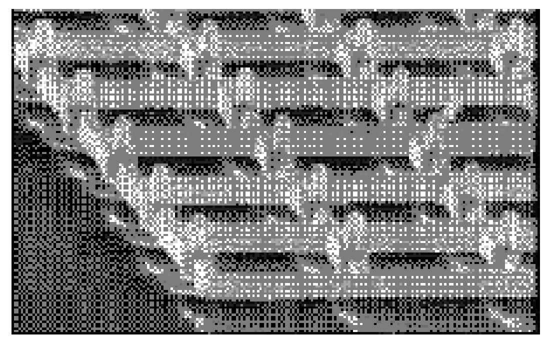
•Select basis behaviors
•Compose and modify behaviors

Distributed Manipulation





Active Surfaces (A. Berlin et al.)



Cornell Micro-Cilia (B. Donald)

SAL tools predict behaviors and synthesize control policy

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Tasks Suitable for Spatial Aggregation

- Explanation generation
- Computer-aided tutoring
- Fault diagnosis and prediction
- Scientific data mining
- Design problems involving complex geometry

Conclusion

- Extract structures as communicable knowledge is the central problem in spatio-temporal data analysis
- Spatial Aggregation is an effective way for discovering structures