Schemas & Cooperative Computation

Reading:

TMB2:

Sections 2.1, 2.2, 4.2 (on HEARSAY), 5.2 and 5.3.

HBTNN:

Schema Theory

Reactive Robotic Systems

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Archinect podcast: “Brain Space: Neuroscience and Architecture,” http://archinect.com/news/article/149968040/brain-space-one-to-one-37-with-michael-arbib-former-vice-president-of-the-academy-of-neuroscience-for-architecture

USC Viterbi School of Engineering video: “55 years of Brains, Machines & Mathematics,” https://youtu.be/4tYRxmOUrss.

Structure & Function

Structure: Neuroscience has a well-established terminology for levels of *structural* analysis (e.g., brain region, layer/module/column/circuit, neuron, compartment, channel, ...) but pays little attention to the need for a *functional* vocabulary.

Function: It is usual to pick some overall function (vision, say) and then immediately seek a structural grounding for its analysis, trying to establish the role of specific regions or circuits in achieving that function.

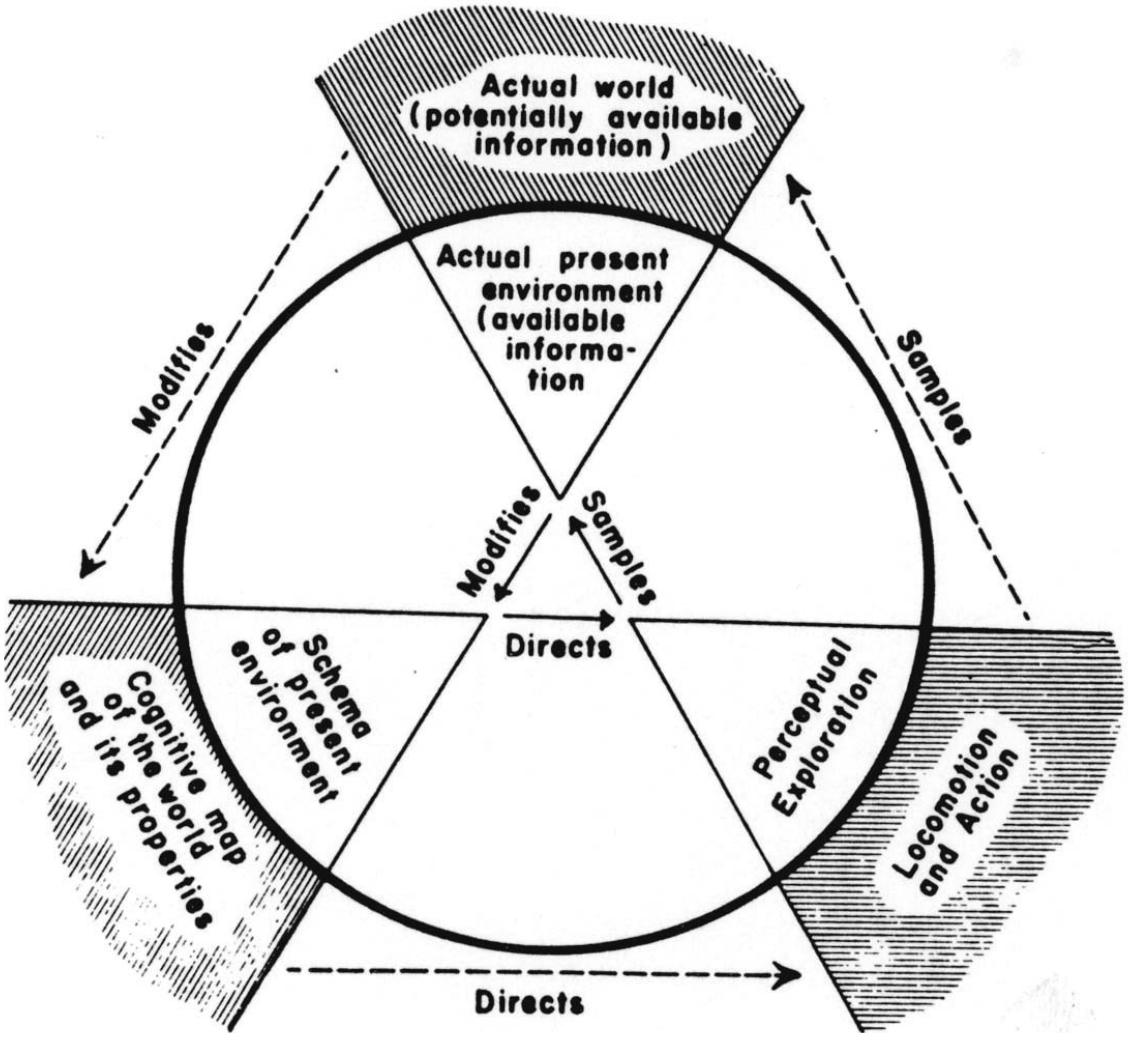
Schema theory provides a rigorous analysis of behavior in terms of the interaction of functional units called ***schemas.***

- Schemas provide the units for distributed, adaptive computation – both for Brain Theory and AI/Robotics – which proceeds via competition and cooperation rather than strict serial control.

Schema theory requires no prior commitment to the localization of each schema, but schemas can be linked to a structural analysis as and when this becomes appropriate.

Action-Oriented Perception: The Action-Perception Cycle

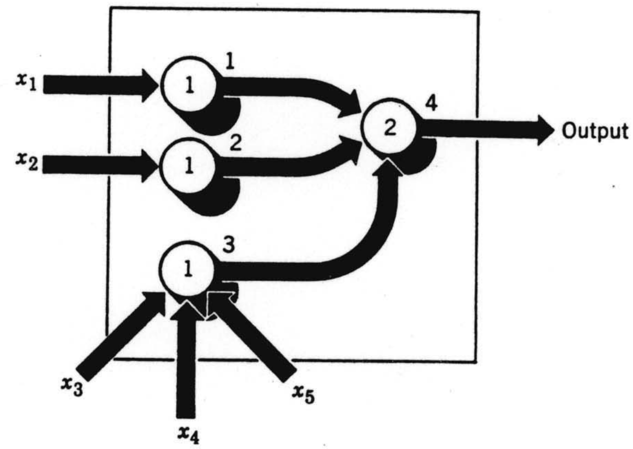
Neisser
1976

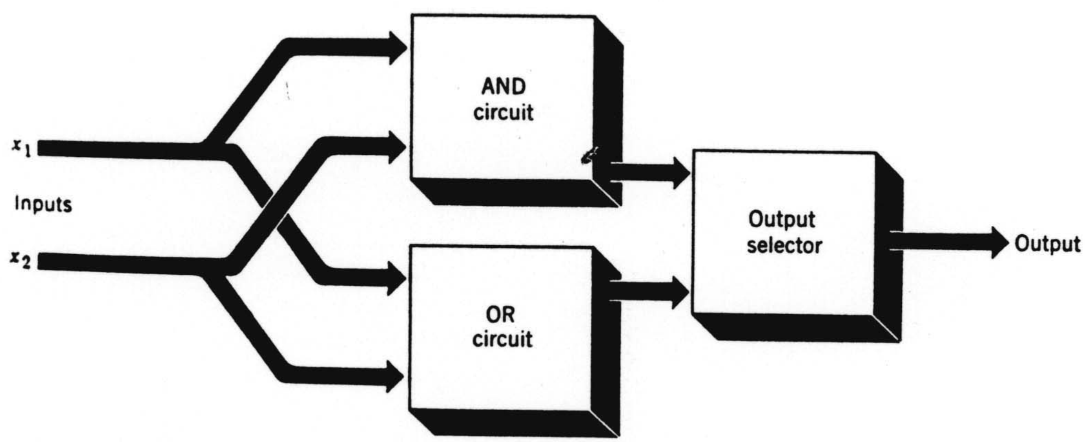


Structure Versus Function

Two systems with the same function but with different structure:

Their external behavior is identical: they can only be told apart by “lesions” or by monitoring internal variables



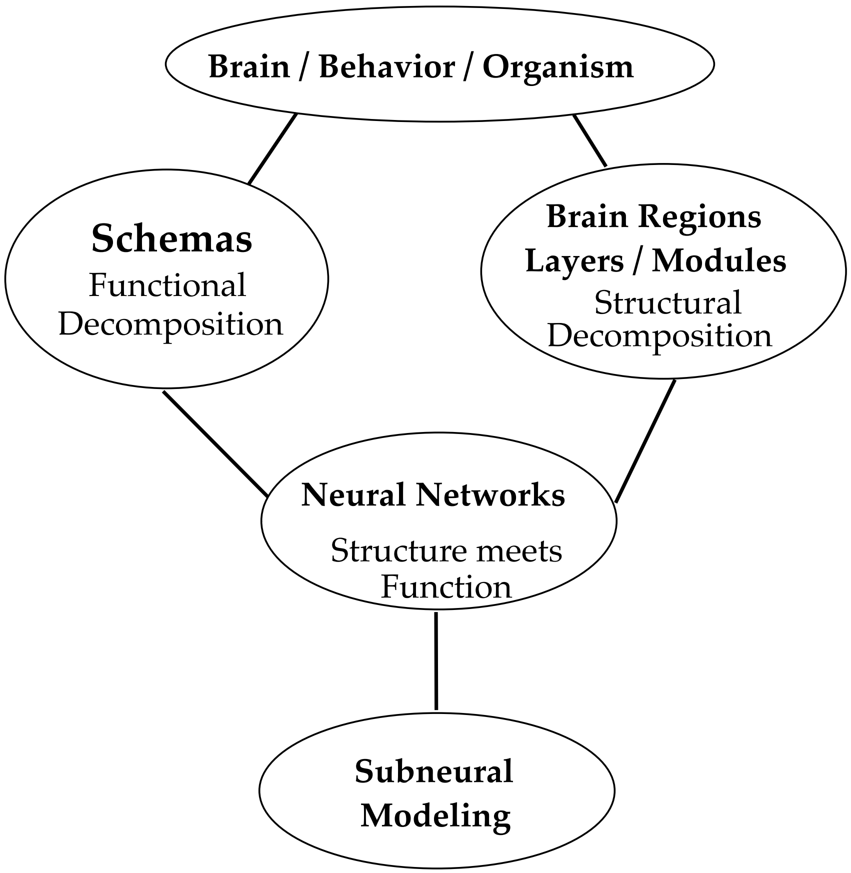


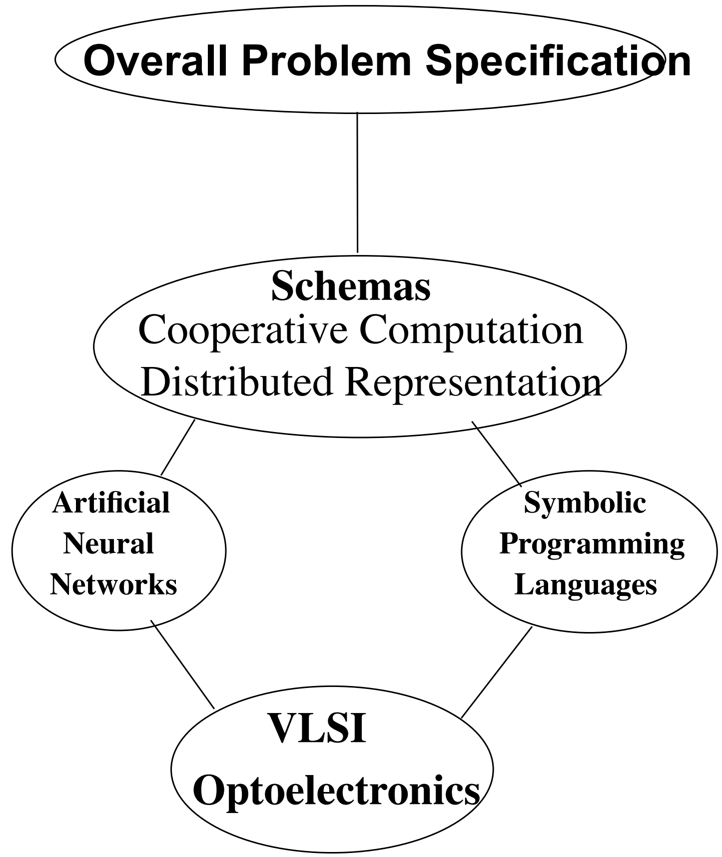
What are Schemas?

Schemas are

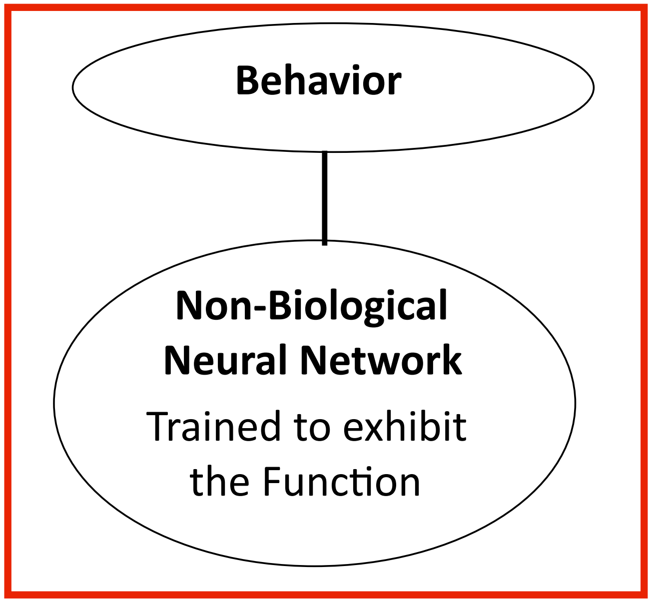
- functional units (intermediate between overall behavior and neural function) for analysis of cooperative competition in the brain
- program units especially suited for a system which has continuing perception of, and interaction with, its environment
- a programming language for new systems in computer vision, robotics and expert systems
- a bridging language between Distributed AI and neural networks for specific subsystems

Hierarchies in Brain Theory and Distributed AI



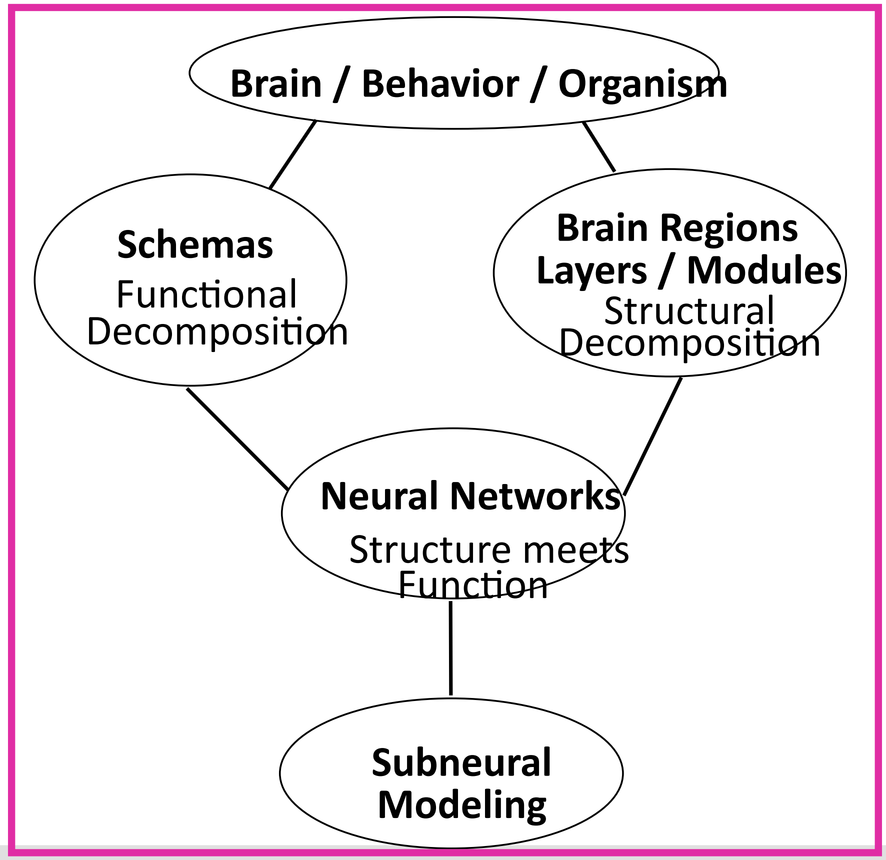


From Connectionism to Computational Neuroscience via Structure and Function



Connectionism: constraints include response rates and errors for different stimuli

Computational Neuroscience: model must explain interaction of components at some level(s)



Perceptual And Motor Schemas

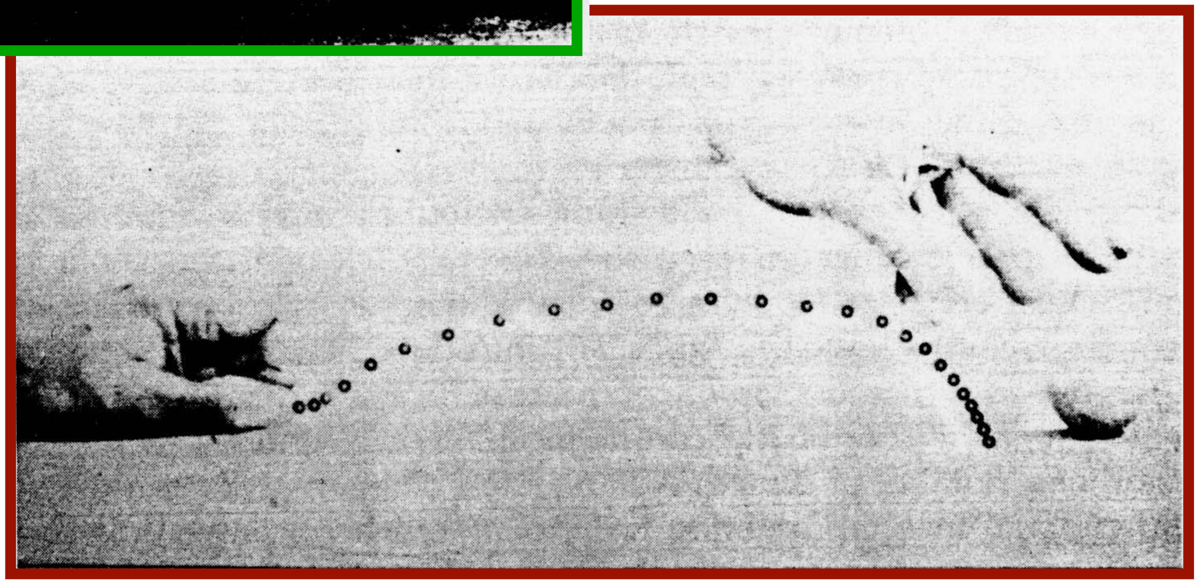
A ***perceptual schema*** embodies the process whereby the system determines whether a given domain of interaction is present in the environment.

- A *schema assemblage* combines an estimate of environmental state with a representation of goals and needs

The internal state is also updated by knowledge of the state of execution of current plans made up of ***motor schemas***

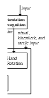
- these are akin to control systems but distinguished by the fact that they can be combined to form *coordinated control programs*

Preshaping While Reaching to Grasp



(Jeannerod and Biguer, 1979)

Hypothetical coordinated control program for reaching and grasping



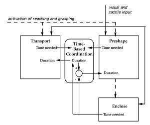
Perceptual
Schemas

Motor
Schemas

Dashed lines — activation signals; solid lines — transfer of data.

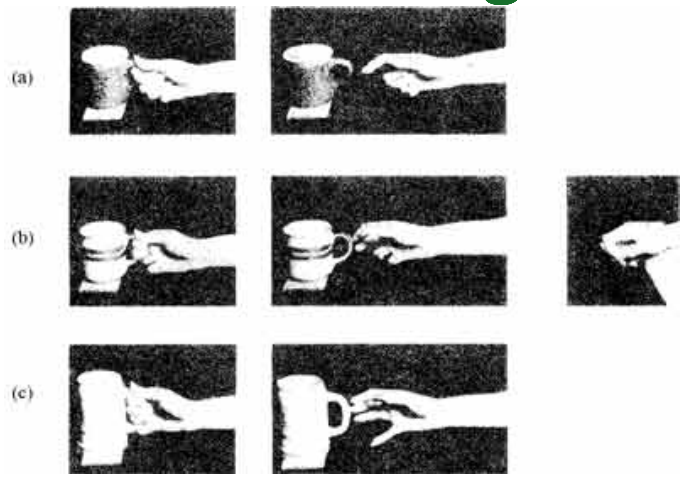
(Adapted from Arbib 1981)

Models can be falsified and revised even at the Schema Level



An overview of a later model of the motor schemas, and their coordination through timing, for reaching and grasping
(Hoff and Arbib 1992)

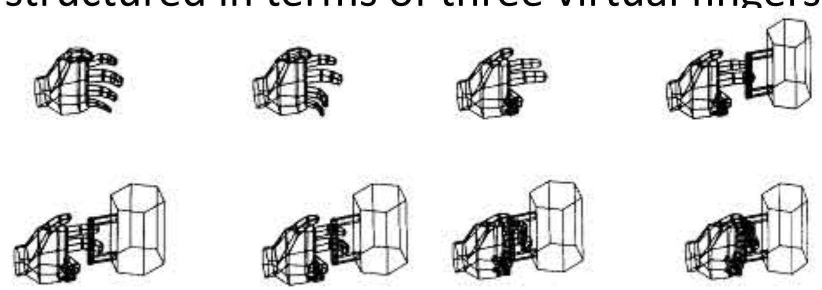
Virtual Fingers



The possible hierarchical structure of schema programs.

- VF 1 (virtual finger 1) is the thumb;
- VF 2 comprises the 1, 2, or 3 fingers that are slipped through the handle; while
- VF 3 comprises the remaining fingers.

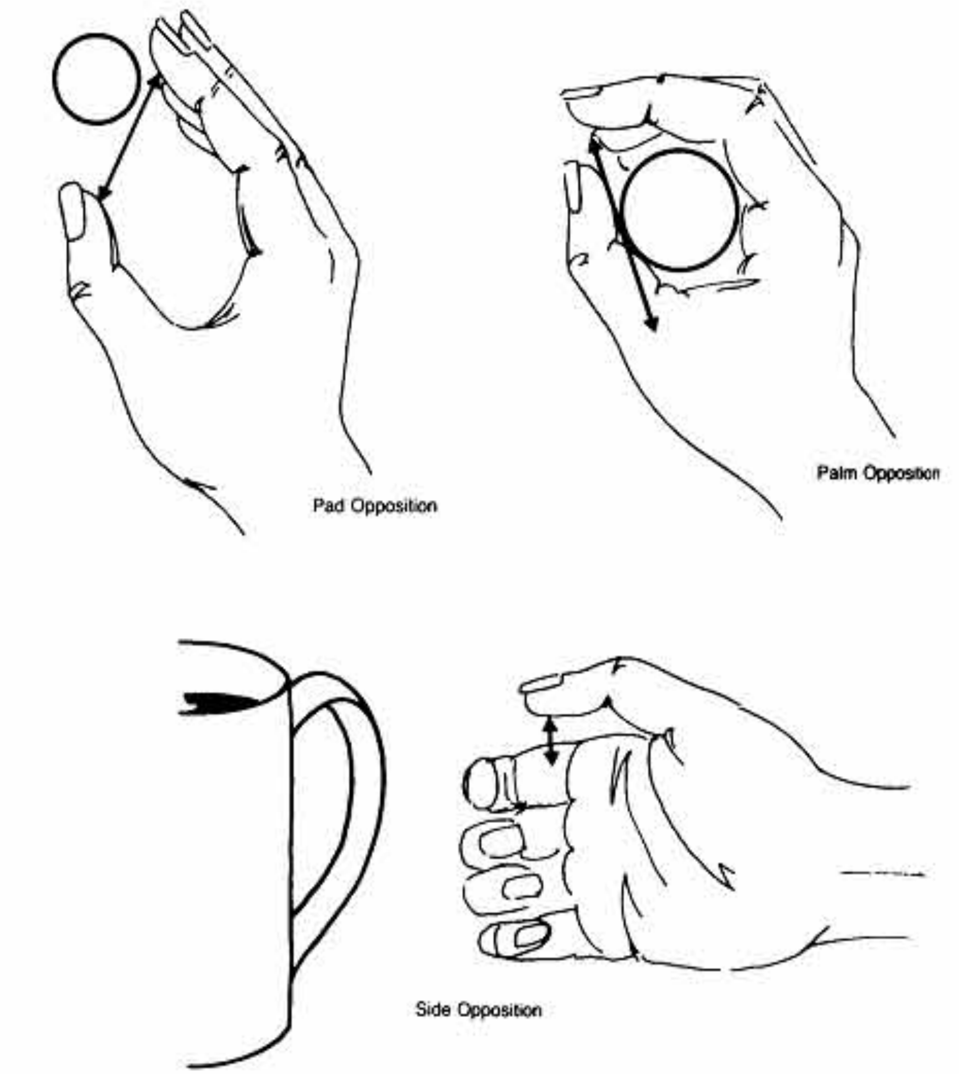
Arbib, Iberall, and Lyons 1985 hypothesize that the brain controls the movement by using schemas which are structured in terms of three virtual fingers.



Opposition Space

Iberall, Bingham and Arbib 1986 showed how **opposition space** could provide coordinate systems for the structural description of the schemas involved in manipulation.

An object may have different representations appropriate to different tasks; and, within such a representation, different coordinate systems may be set up for different parts of the object and/or different stages of task execution. It is an important challenge to explore the "neural reality" of such coordinate systems.



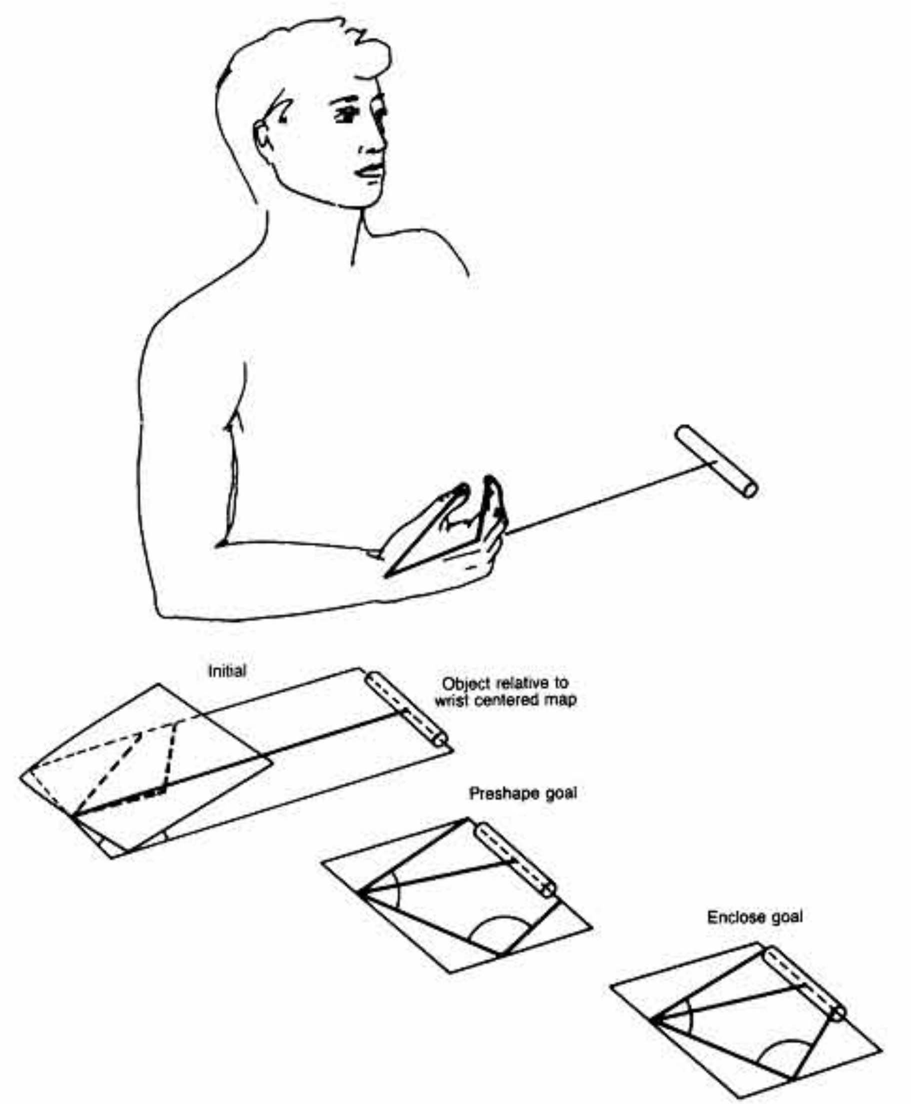
Planning Runs “Backwards”

In planning:

- Compute the final shape of the ha
  transport by the arm of the hand)

In execution:

- The enclosing of the hand upon th



Neural Schema Theory

Neural schema theory is a specialized branch of schema theory, just as neuropsychology is a specialized branch of psychology.

- A given schema, defined functionally, may be distributed across more than one brain region
- A given brain region may be involved in many schemas.

Hypotheses about the localization of (sub)schemas in the brain may be tested by lesion experiments.

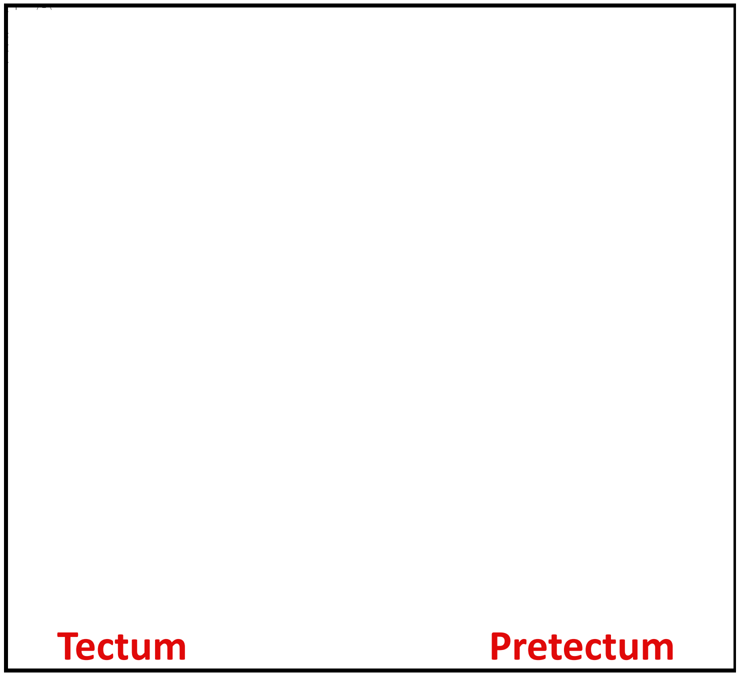
Schemas for Pattern-Recognition in the Toad

One task of the tectum: directing the snapping of the animal at small moving objects

Also: the frog jumps away from large moving objects and does not respond when there are only stationary objects.

Initial Hypothesis: the animal is controlled by two schemas:

- one for prey catching which is triggered by the recognition of small moving objects, and
- one for predator avoidance which is triggered by large moving objects.



But … lesioning pretectum does not yield the predicted effect on behavior.

Schemas for Pattern-Recognition in the Toad

Tectum

Pretectum

Revised Hypothesis: the animal is controlled by two schemas:

- one for prey catching which is triggered by the recognition of ***any*** moving object, and
- one for predator avoidance which is triggered by large moving objects and also inhibits the schema for prey catching

Moral:

Even gross lesion studies can distinguish between alternative top-down analyses of a given behavior.

Such an analysis can be refined by more detailed behavioral and neurophysiological studies. (Supplementary reading: TMB2, Sec 7.3.)

Localization of Schemas

In Brain Theory, a given schema, defined functionally, may be distributed across more than one brain region; conversely, a given brain region may be involved in many schemas.

A top-down analysis may advance specific hypotheses about the localization of (sub)schemas in the brain, and these may be tested by lesion experiments, with possible modification of the model (e.g., replacing one schema by several interacting schemas with different localizations) and further testing.

In Distributed AI, schema instances (or **agents** – see HBTNN: Multiagent systems) must be allocated to a limited set of processors, thus raising issues of (distributed) scheduling.

Schemas versus Schema Instances

A schema may be instantiated to form multiple *schema instances*.

Example: given a schema that represents generic knowledge about some object, several instances of the schema may be activated to subserve our perception of a scene containing several such objects.

- Schema instances can become *activated* in response to certain patterns of input from sensory stimuli (data driven) or other schema instances that are already active (hypothesis driven).
- The *activity level* of an instance of a perceptual schema represents a "confidence level" that the object represented by the schema is indeed present; while that of a motor schema may signal its "degree of readiness" to control some course of action.

Computational and cognitive neuroscience?

Cognitive Neuroscience

Bringing the techniques of cognitive science to bear on the study of how the brain provides mechanisms for processes of cognition.

Computational Neuroscience

Regions of the brain - visual cortex, hippocampus, spinal cord, and so on - are very distinctive.

Thus, computational neuroscience must model the brain as a network of specialized computers at any of a variety of levels including

Level (i) the "cooperative computation" that links various brain regions in subserving a variety of behaviors,

Level (ii) the way in which the circuitry of a specific region fits it for certain tasks, and

Level (iii) the intricate properties of individual neurons rooted in membrane biophysics and neurochemistry.

Cognitive (non-neuro) science has a Level (o) in which cognitive processes are given computational models without regard for neural correlates.

Conventional Computers vs. Cooperative Computation

Conventional computers store data passively, to be retrieved and processed by some central processing unit.

Schema theory explains behavior in terms of the interaction of many concurrent activities:

Schemas are the "programs" for ***cooperative computation –*** based on the competition and cooperation of concurrently active agents (schema instances)

- ***Cooperation***: yields a pattern of "strengthened alliances" between mutually consistent schema instances that allows them to achieve high activity levels to constitute the overall solution of a problem (as perceptual schemas become part of the current short-term model of the environment, or motor schemas contribute to the current course of action).
- ***Competition***: instances which do not meet the evolving (data-guided) consensus lose activity, and thus are not part of this solution (though their continuing subthreshold activity may well affect later behavior).

Corollary: Knowledge receives a distributed representation in the brain. A multiplicity of different representations must be linked into an integrated whole, but such linkage may be mediated by distributed processes of competition and cooperation. **There is no one place in the brain where an integrated representation of space, for example, plays the sole executive role in linking perception of the current environment to action**

Schema theory is a Learning Theory, Too

Jean Piaget (Swiss "Genetic Epistemology" – *The Construction of Reality in the Child, etc.)*:

Assimilation: *understanding the current situation in terms of existing schemas*

Accommodation: *creating new schemas when assimilation fails.*

In our coordinated control program/schema assemblage framework:

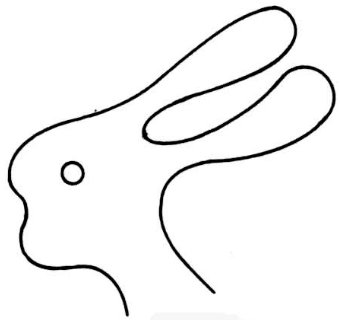
New schemas may be formed as assemblages of old schemas

Tunability of schema-assemblages allows them to start as composite but emerge as primitive

See TMB2 Section 5.4 for a "computational neo-Piagetian" approach to language acquisition.

However, the learning models we look at in this course are primarily based on "learning rules" for synaptic modification.

The Famous Duck-Rabbit



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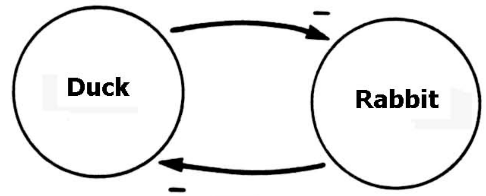
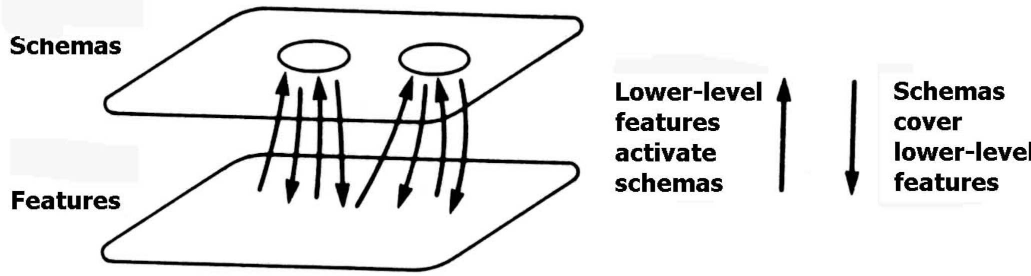


(b)

From Schemas to Schema Assemblages



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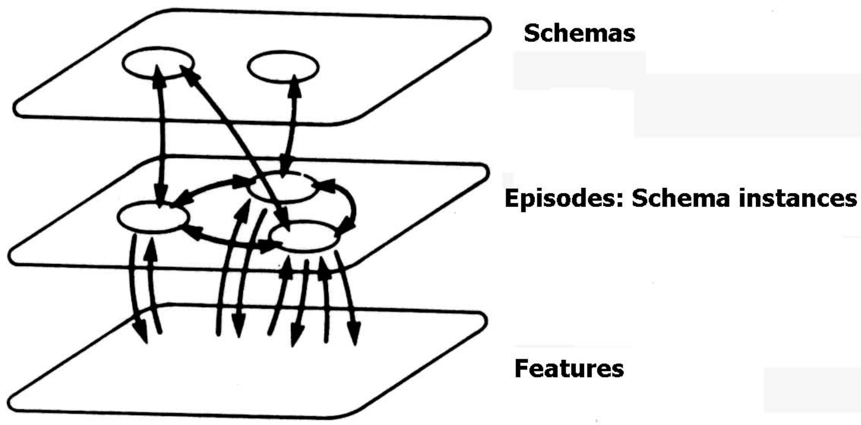
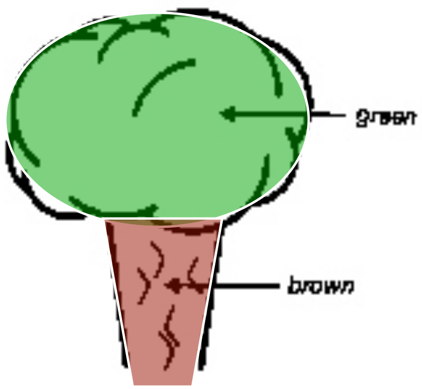


(d)

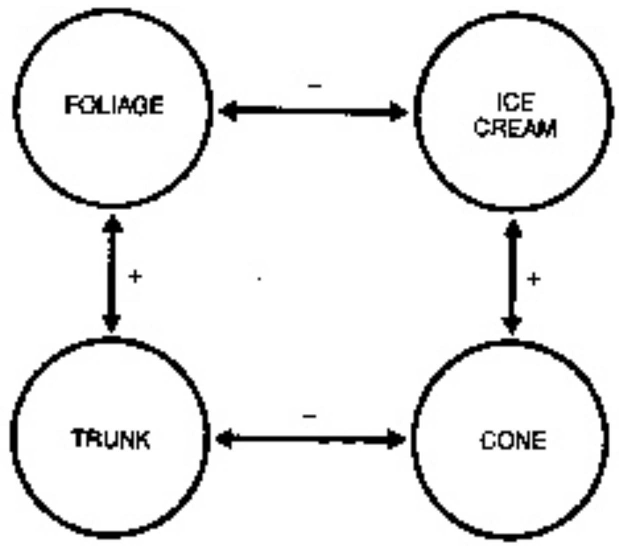
Competition and Cooperation Between Perceptual Schemas

Tree



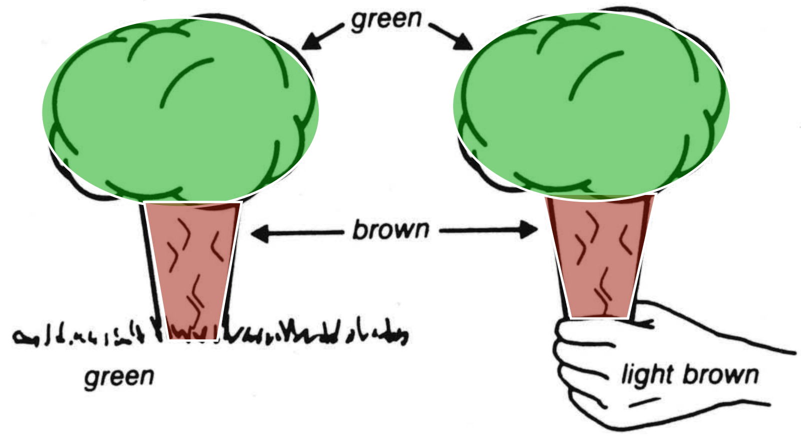
or Ice Cream Cone?

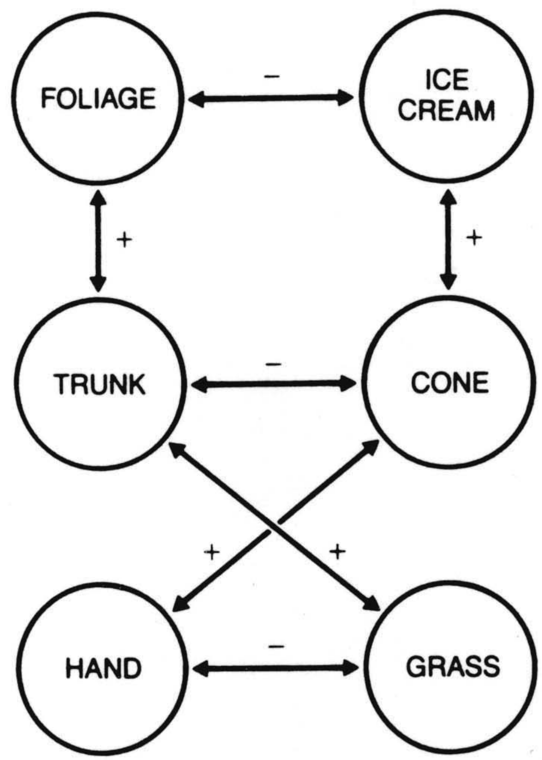
Cooperation: signs
(specific knowledge)



Competition: - signs
(general constraint)

Bringing in Context





Extended Scene Perception

Attention-based analysis: Scan scene (attention), accumulate evidence from detailed local analysis at each attended location.

Main issues:

- what is the internal representation?
- how detailed is memory?
- do we really have a detailed internal representation at all!!?

Gist and Scene Perception

We work both

- ***down*** from the gist and
- ***up*** from the objects.

Incompleteness of memory:

how many windows in the Taj Mahal?

despite conscious experience of picture-perfect, iconic memorization.

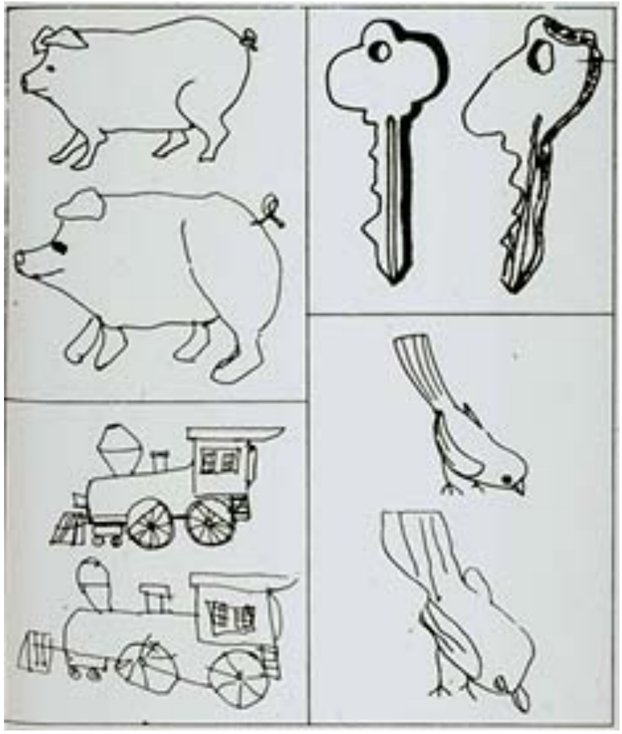
Yet we can often extract the ***gist*** of a scene with great rapidity (120 ms)

- to classify "generic aspects" of entire scenes or do simple recognition tasks; can only shift attention twice in that much time (Recall slides on bottom-up versus top-down attention)
- thus setting "hypotheses" that can guide our interpretation of the data as we seek to understand specific questions.

Clinical Studies

Studies with patients with some visual deficits strongly argue that tight interaction between where and what/how visual streams are necessary for scene interpretation.

Visual agnosia: can see objects, copy drawings of them, etc., but cannot recognize or name them!

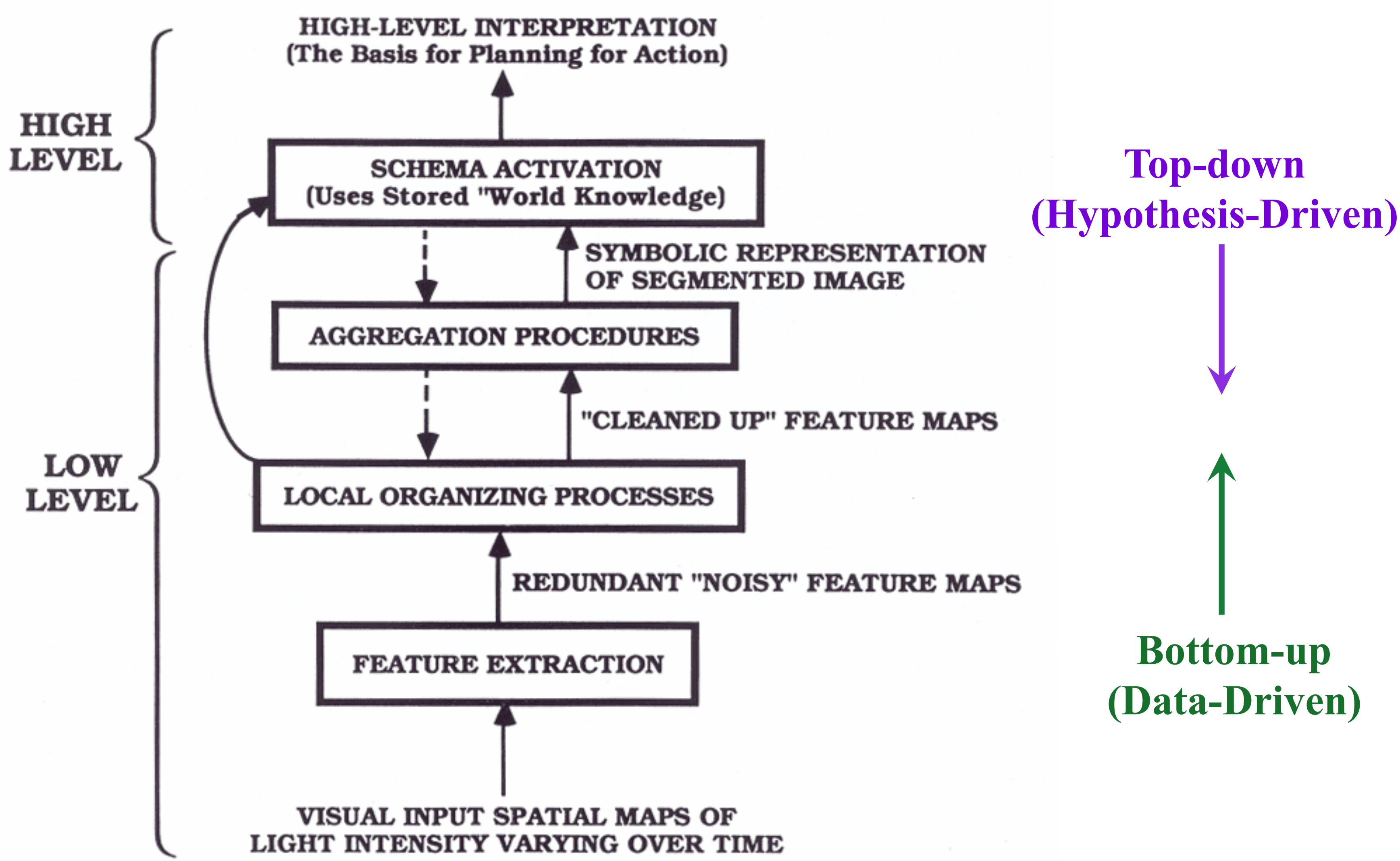


Dorsal agnosia: cannot recognize objects if more than two are presented simulta-neously: problem with localization

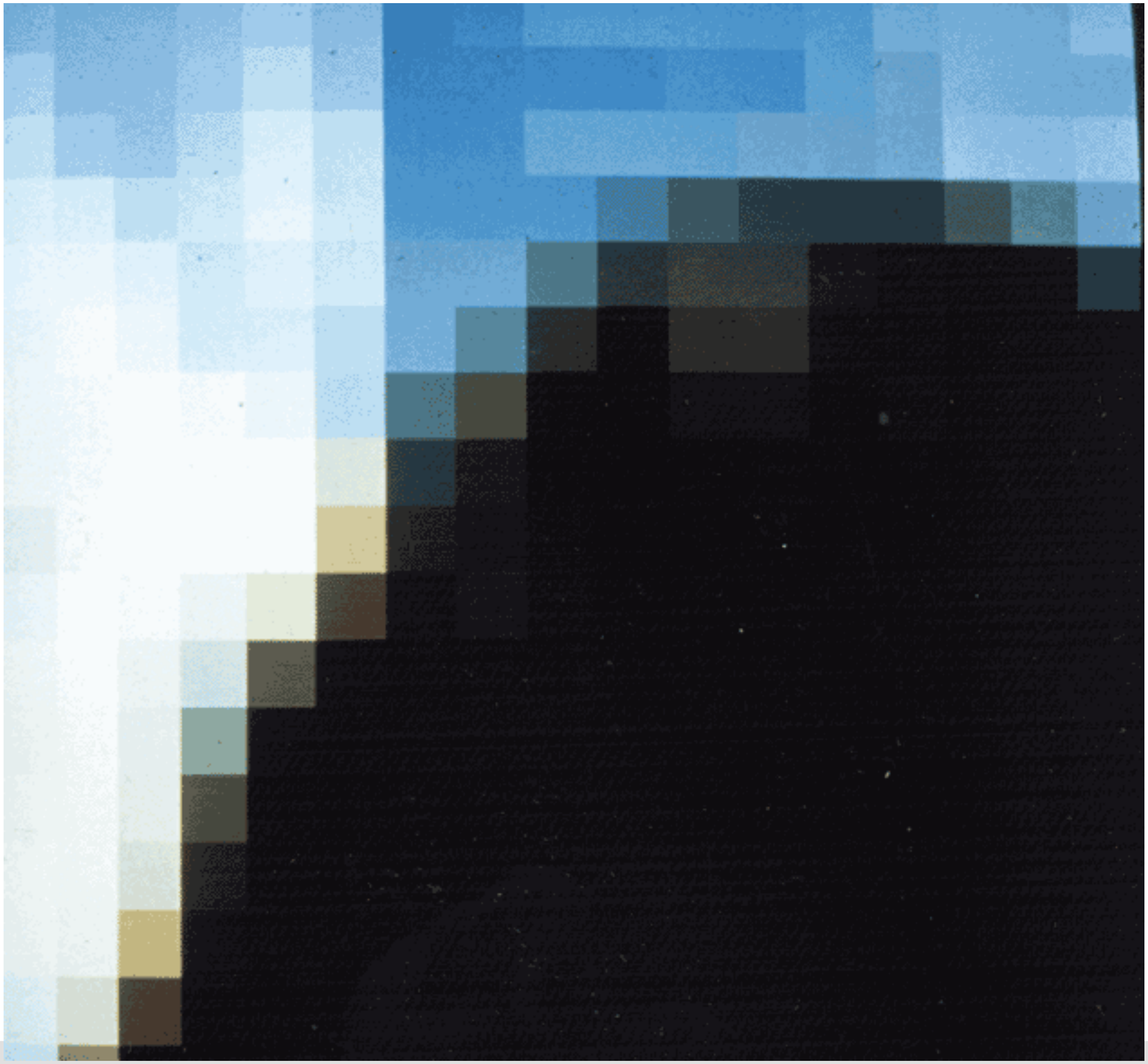
Ventral agnosia: cannot identify objects.

Recall slides of simultanagnosia

Low- versus High-Level Vision



Data-Driven Interpretation May Not Work



Posing a Chicken and Egg Problem

We must seek
islands of
(possibly transient)
reliability

Our Focus: The VISIONS system

Allen Hanson and Edward Riseman of UMass

(a classic, but not the state of the art)

The Style of the VISIONS systems

A distributed "expert system" for visual scene interpretation

High-level vision involves interleaving of multiple processes:

a cooperative computation in which each schema is invoked (instantiated) where appropriate, possibly many times

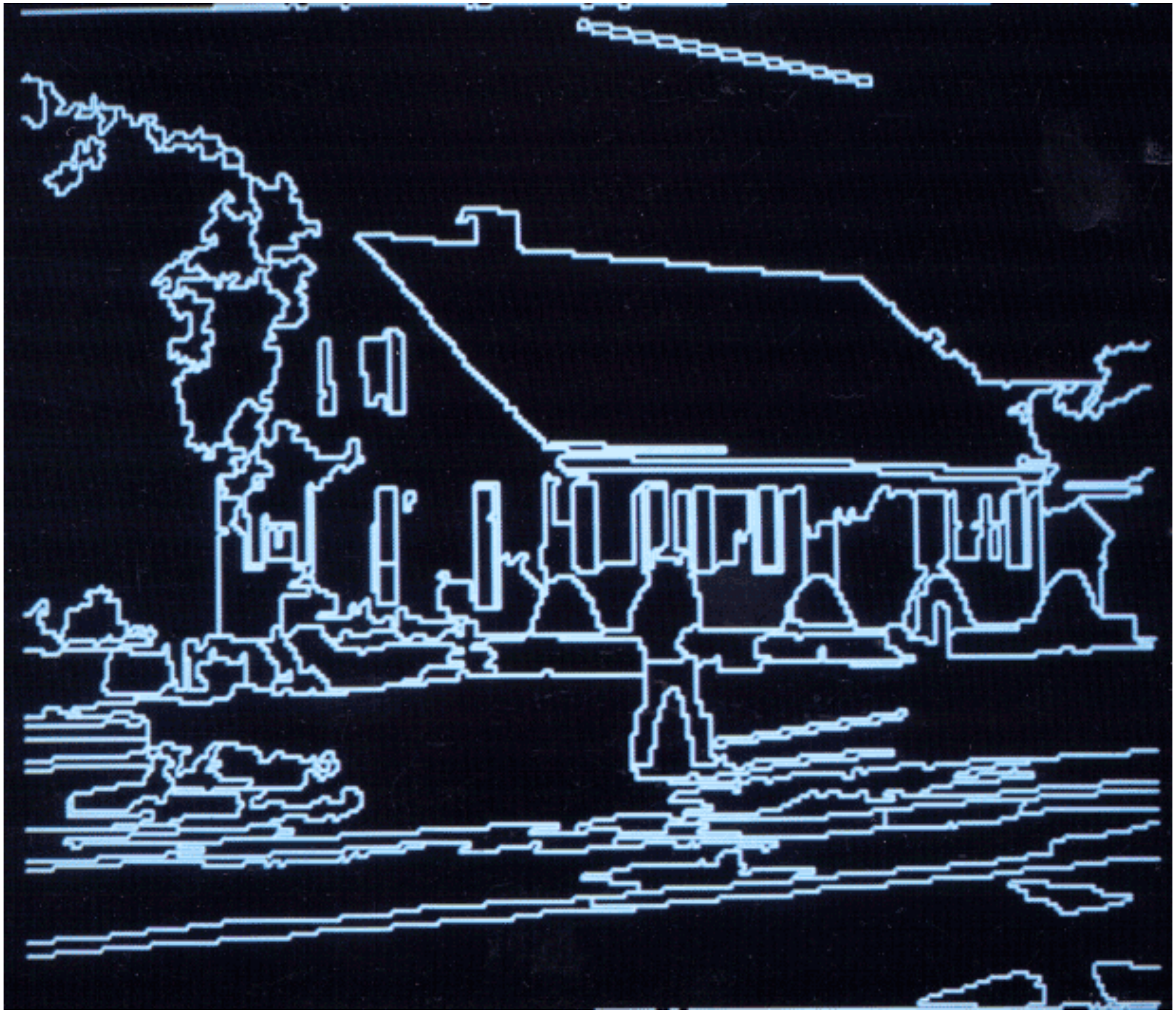
with hypotheses being generated and discarded until the system converges on as good an interpretation as it is able to give with the facilities available to it.

This style:

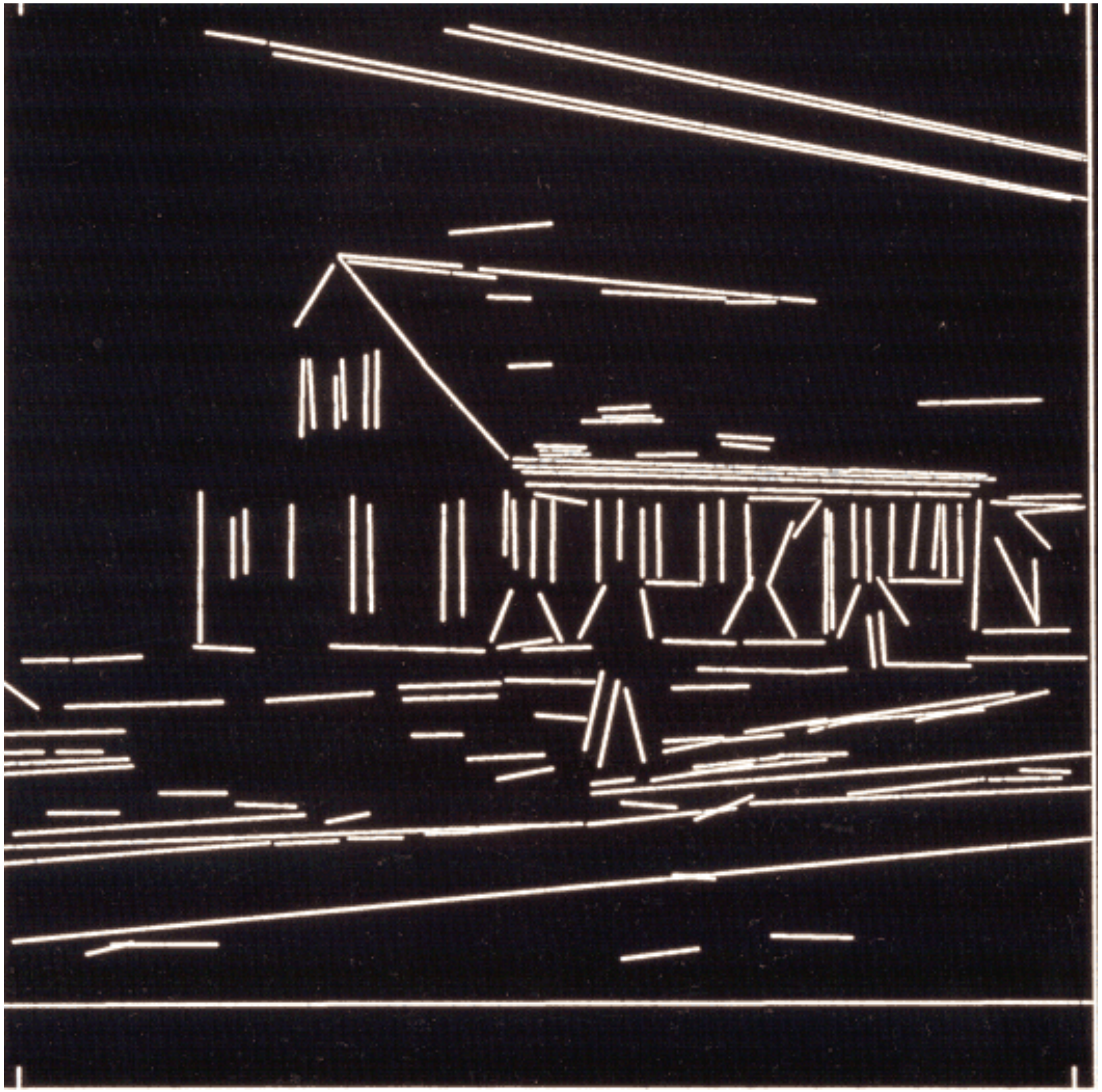
- characterizes the perceptual mechanisms of brains, and
- will provide the style for future developments integrating perceptual systems for robot control.

This is **distributed** rather than **parallel** computation

Segmentation by Growing Edges and Regions



Long-Line Extraction



Another approach to low-level processing – great for extracting those power lines (or are they telephone wires?)

LTM (schemas) versus WM (schema instances)

Long-Term Memory: LTM:

Specialized perceptual schemas for recognizing different objects or controlling various tasks

form a representation of the current scene

Working Memory: WM (Short-Term Memory: STM)

An assemblage of schema instances formed by a combination of:

- **Data-Driven (Bottom-Up) Processing**

  Looking at characteristics of different portions of the image as represented in the low level data

- **Hypothesis-Driven (Top-Down) Processing**

  Passing messages to each other to settle on a coherent interpretation.

Intermediate database for Vision

Two stages of **data-driven processing**:

1. Apply a variety of local processors to come up with
 feature maps which highlights the most likely
 "information-bearing" places within the visual input.

2. Build upon these feature maps to represent
 position and shape of objects

without calling on knowledge about the types of objects.

These yield the **intermediate data base** which

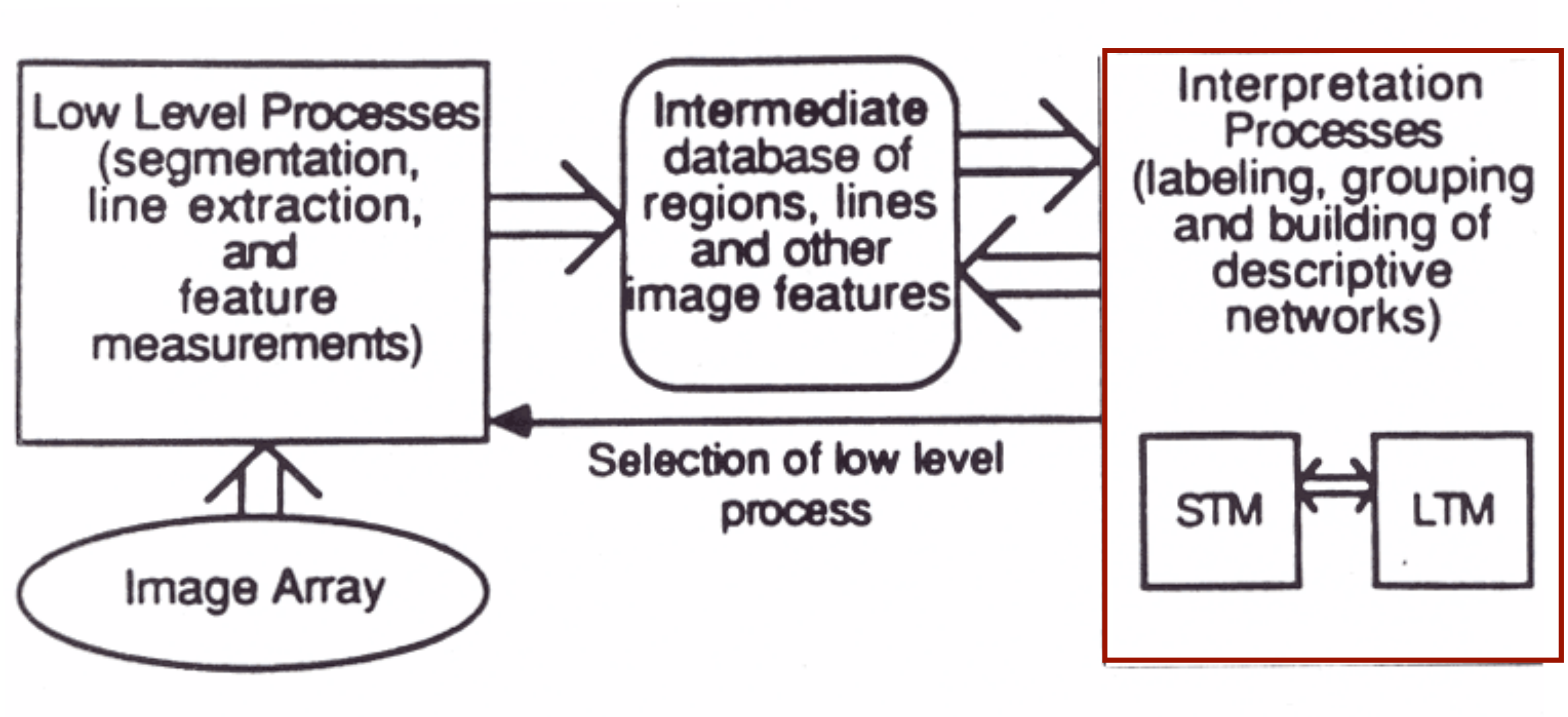
• provides data for high-level vision to act upon, *and*

• can respond to queries from higher levels for further low-level processing.

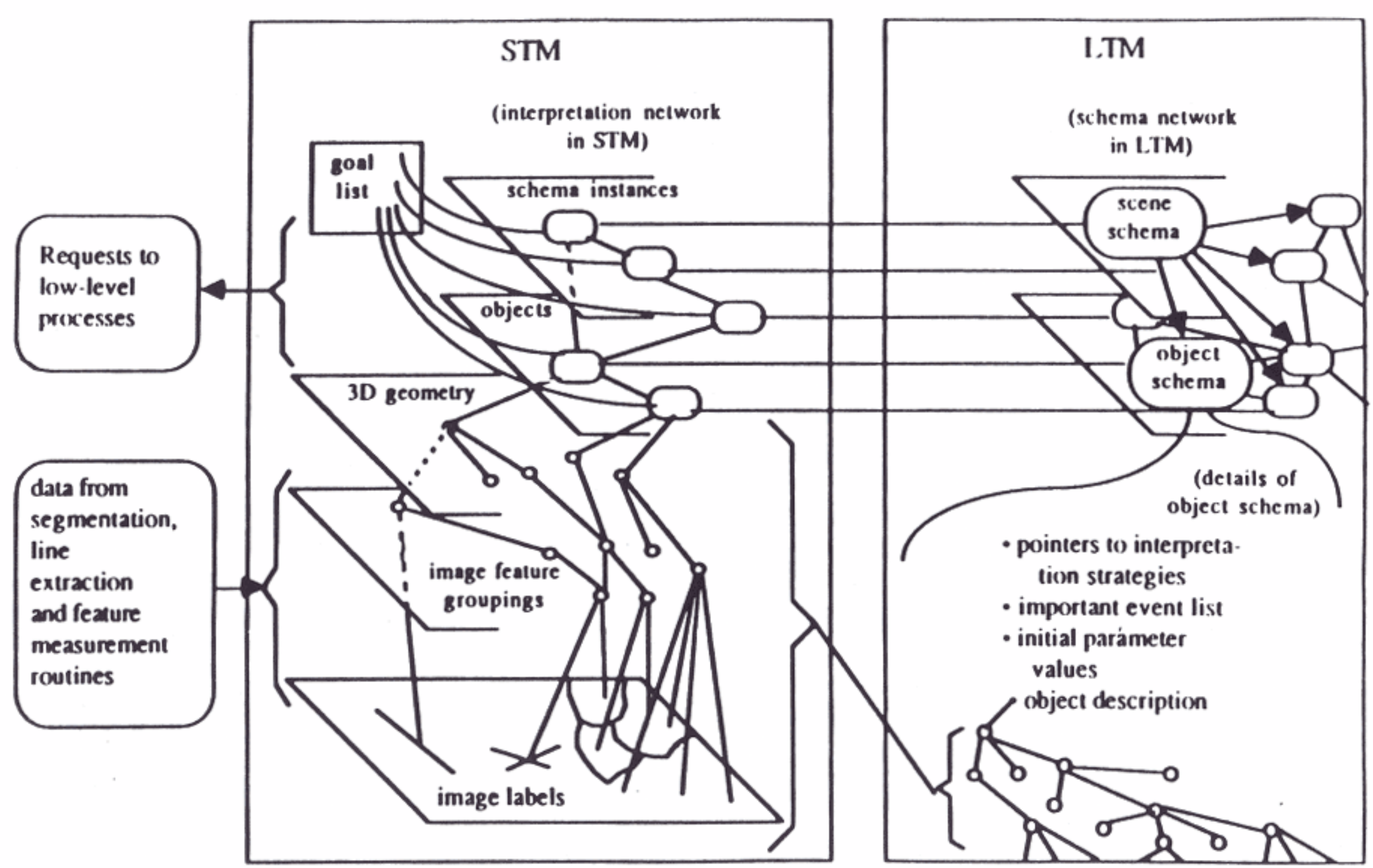
*This intermediate data base may be **distributed**, rather than constituting a single, unitary representation.

cf. Section 7.4 of TMB2 on The Many Visual Systems

I now prefer WM (Working Memory) to STM here:



The VISIONS system



If One Starts Data-Driven …

Need measures effective in assigning a

confidence level

in forming

an initial "data-driven" classification

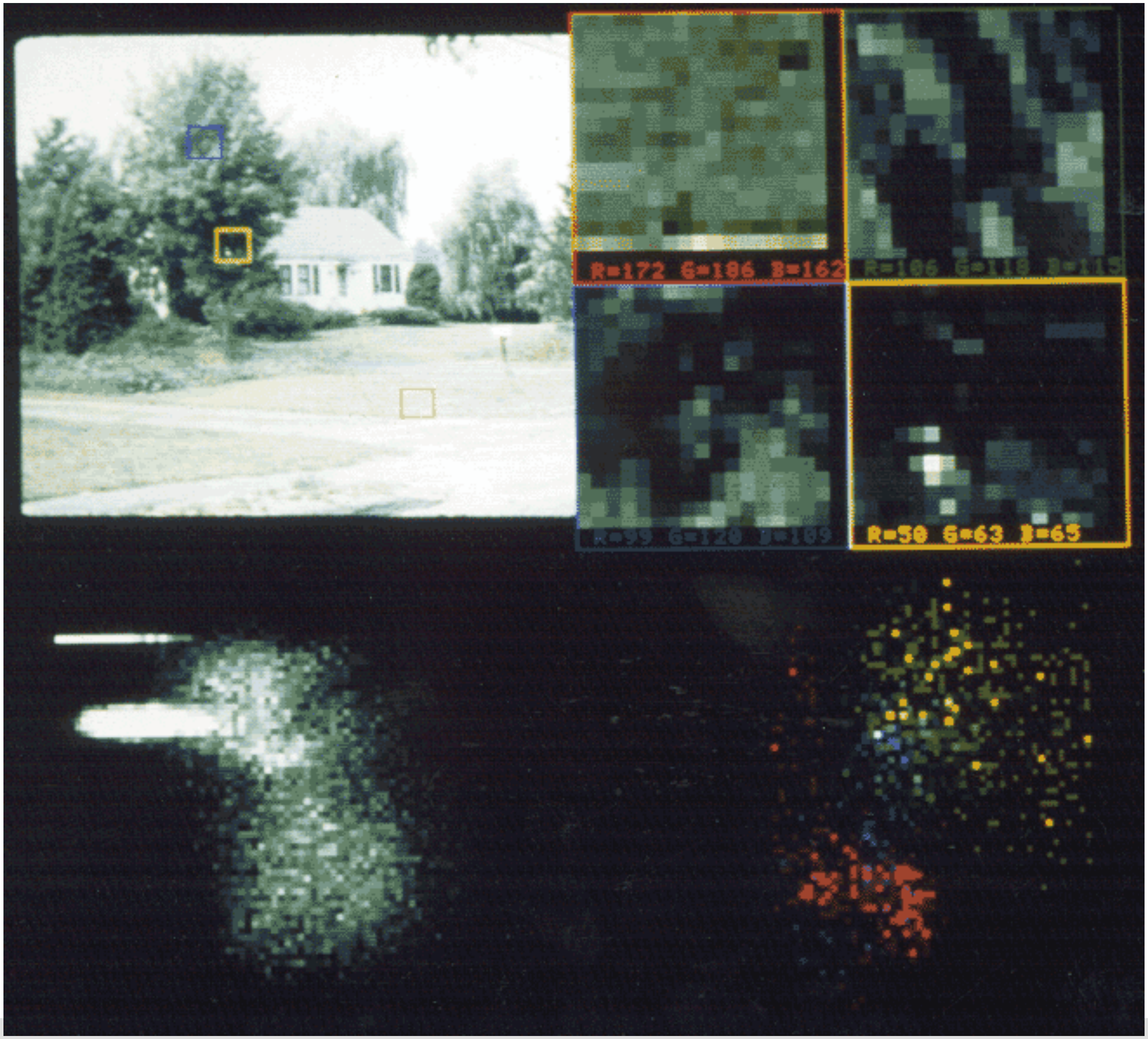
of a region on the basis of local cues.

In general, this will be only the first step and in no way forces the final interpretation.

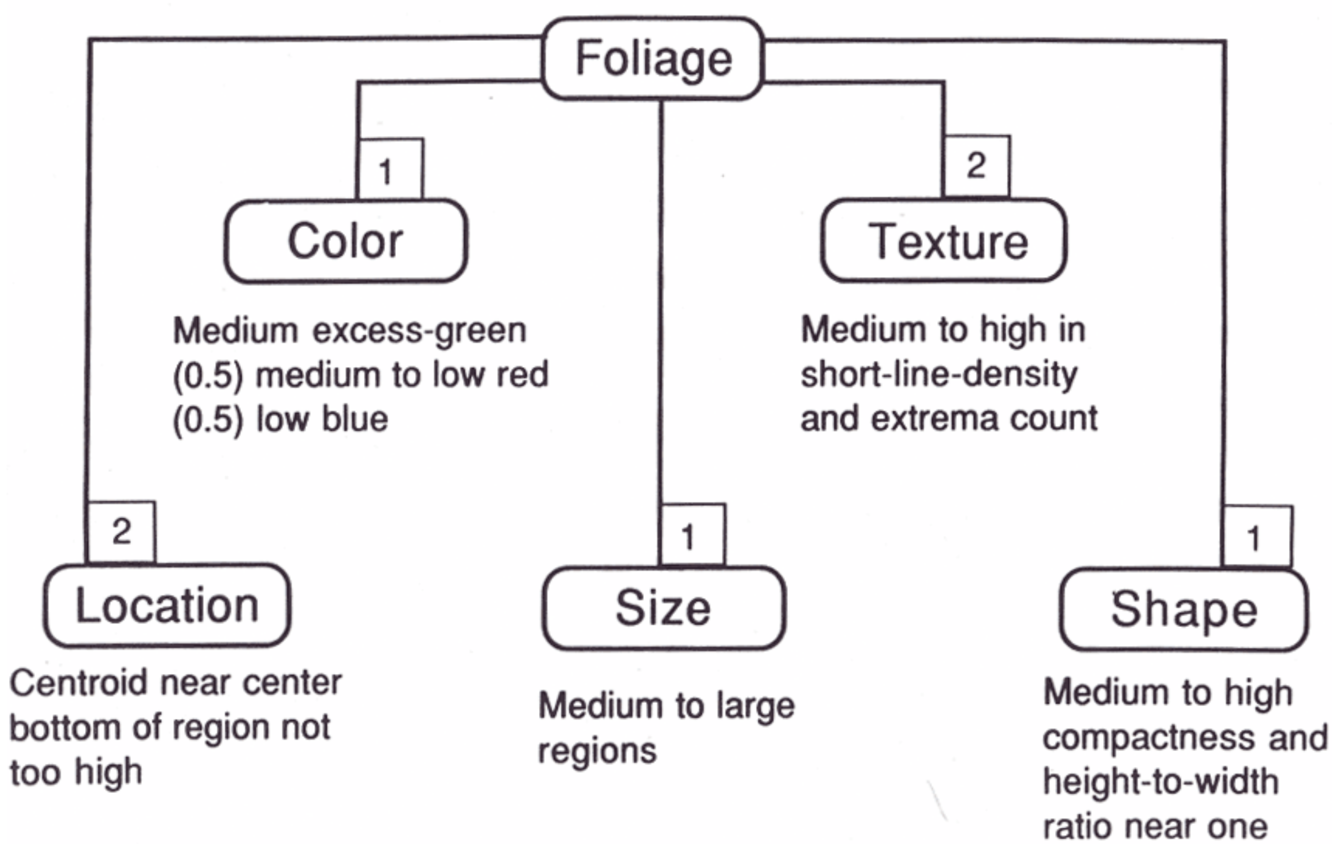
Some object classes have known limits on surface color and texture; in other cases, geometric form and surface appearance may be more useful.

Histogramming Pixel Samples

(Different Image – Why is that OK?)



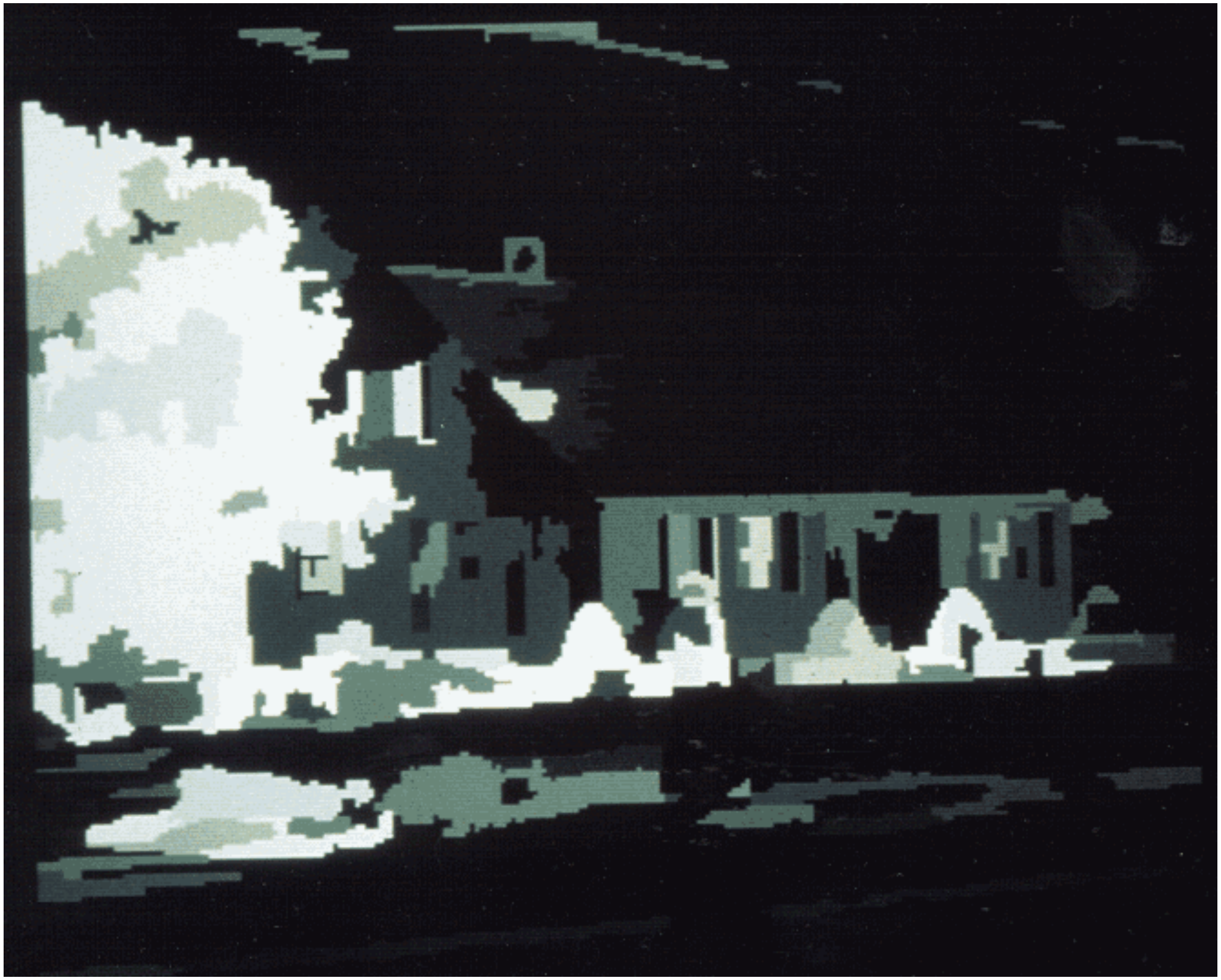
Data-Driven Part of Schema for Foliage



The Example We Will Work With

(but the color is better in the original!)

Data-Driven Confidence Levels for Foliage



Foliage – Data-Driven First Approximation

The Sky – Data-Driven First Approximation

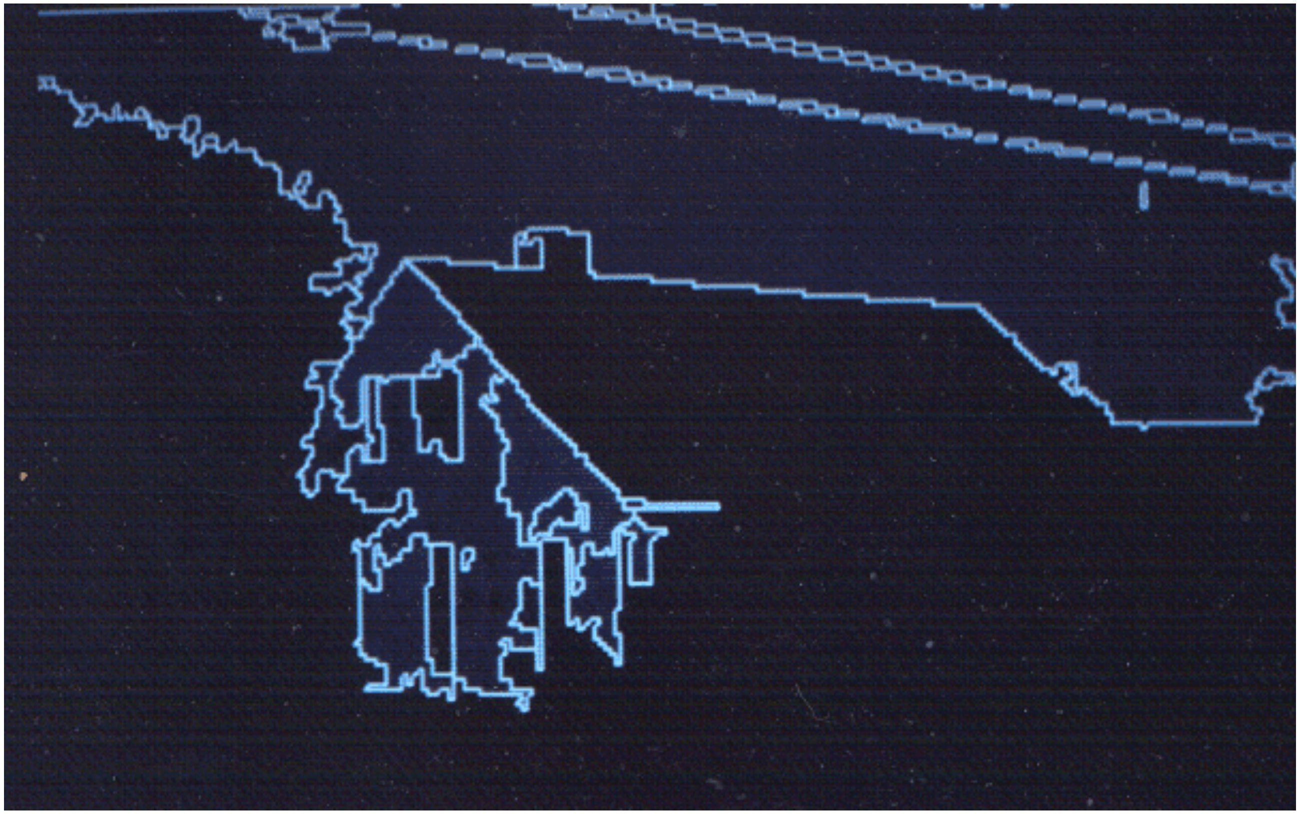
The Roof – Hypothesis-Driven First Approximation

The Walls – Hypothesis-Driven First Approximation

Focusing the Resegmentation

Resegmentation

But why not use this finer segmentation to start with?



Bringing in More Knowledge

- **Cooperative computation is not a one-way process**

Although some low-level processing may be required to initiate high-level schema activity, once this schema activity is underway, it may call for the low-level processing as appropriate.

- **Intelligence can save a lot of work**

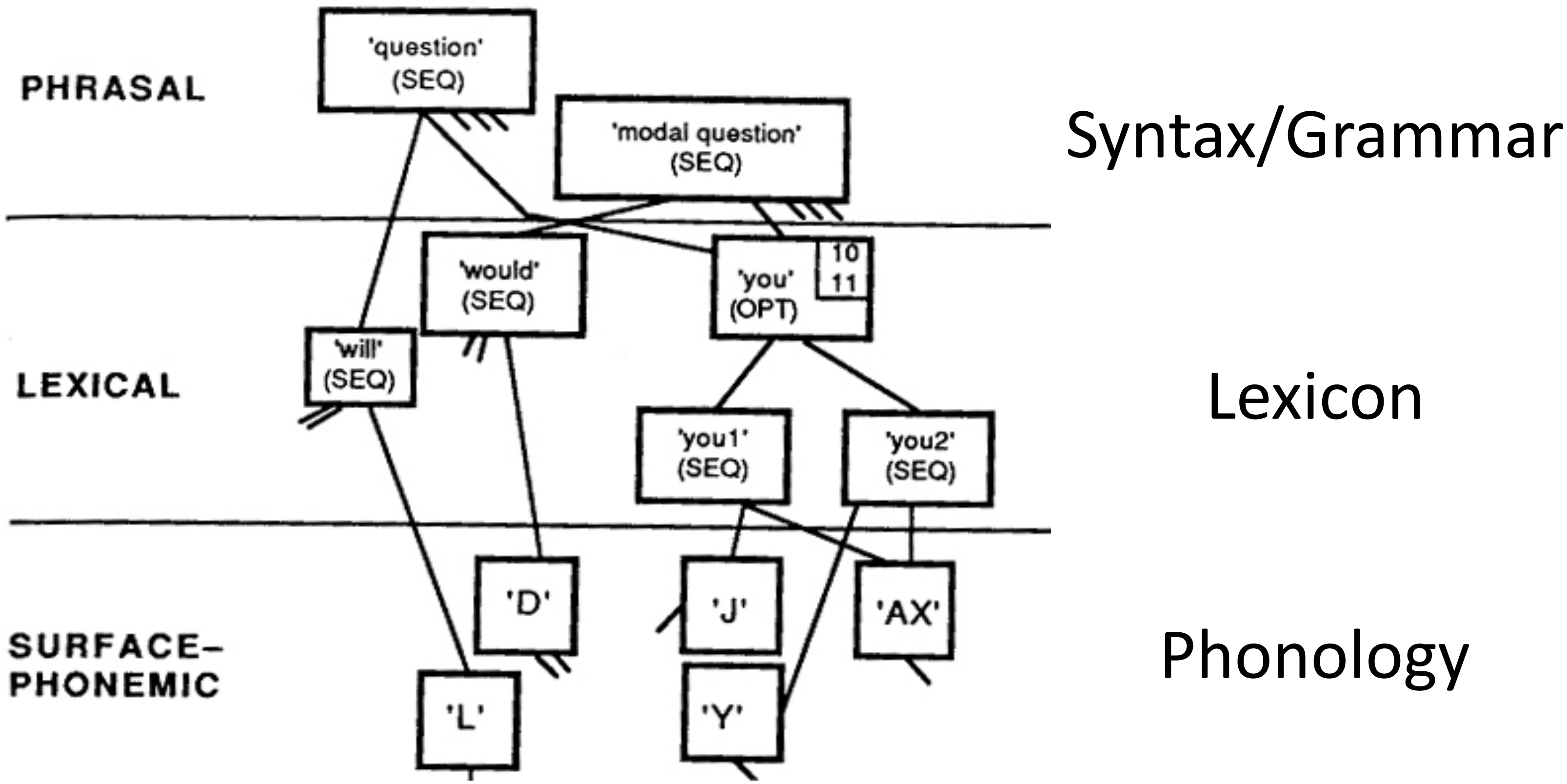
A rather small number of high-level rules can allow us to avoid much expensive low-level processing.

Interpretation may also integrate matching 3D models of geometric structure to line segments in the image, salience, focus of attention, etc.

The End Result

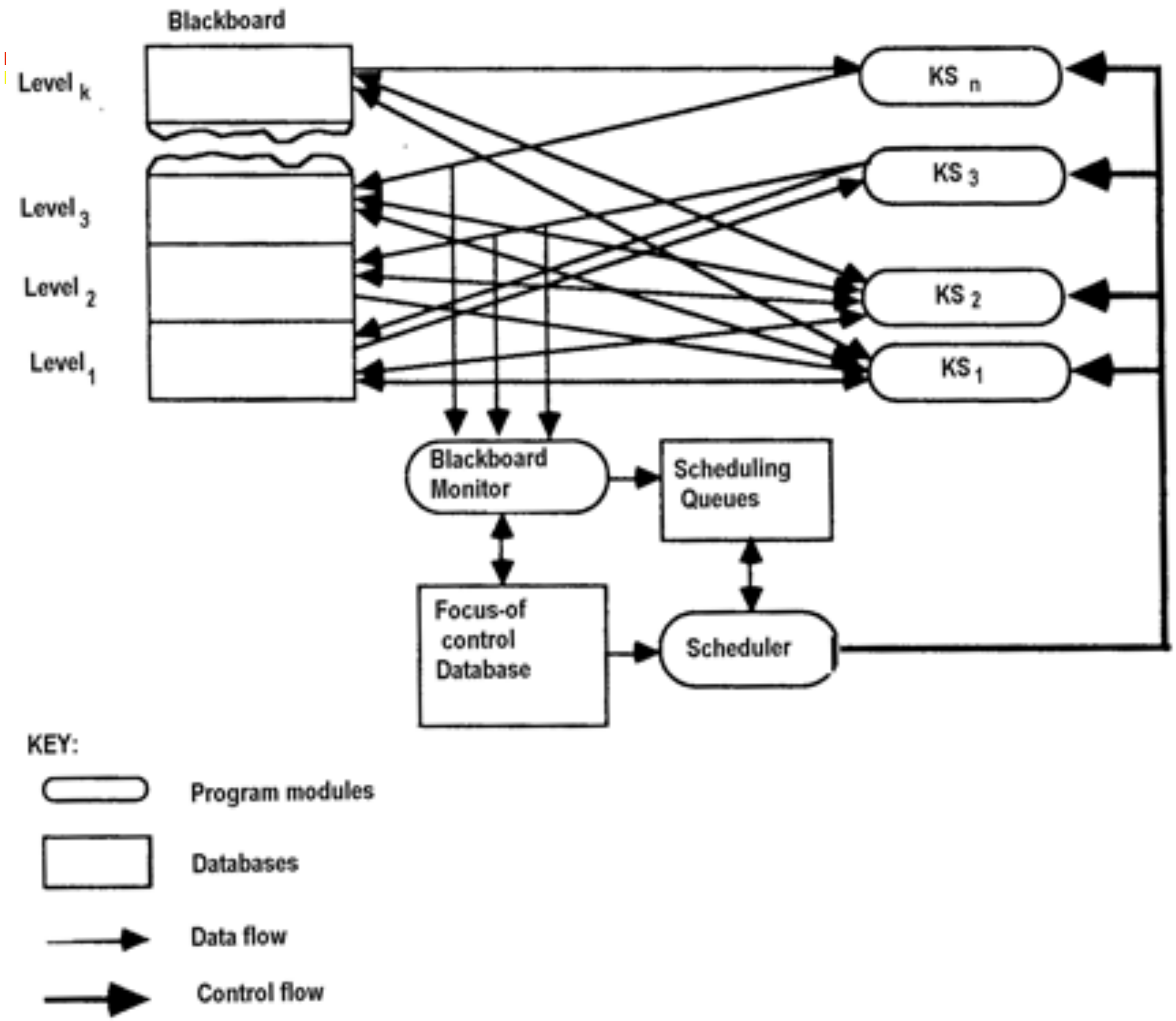
Why is it incomplete?

HEARSAY: Schemas for Speech Understanding
A cooperative computation approach to perception



Different hypotheses on different layers of the blackboard, and with time-varying confidence levels compete and cooperate to cover the speech stream

HEARSAY II (1975)



A Serial Implementation of a Distributed Architecture (Erman & Lesser 1975)

Arbib & Caplan (1979) considered how it might relate to the **interaction of multiple brain regions**

Lecture Goals 1

Schema theory analyzes behavior in terms of the interaction of functional units called *schemas*

Perceptual schemas may form schema assemblages, and motor schemas may combine with perceptual schemas to form coordinated control programs

- Example: The reach to grasp

Neural schema theory offers hypotheses on localization of schemas in the brain and/or their implementation by neural networks

- Hypotheses about localization in the brain may be tested by lesion experiments
  - Example: Frog prey capture and predator avoidance

Cooperative Computation: Defined by competition & cooperation of schema *instances*

- Examples: The duck-rabbit; the effect of context
  - Competition and cooperation may be generic or knowledge-specific

Lecture Goals 2

Gist can be quickly extracted, setting the context for recognizing details of a scene

Low-level versus High-level vision

- Low → High: Bottom-up (Data-Driven)
- High → Low: Top-down (Hypothesis-Driven)
- The need for "islands of reliability"

The VISIONS system for visual scene understanding

- Combines bottom-up and top-down processing; competition and cooperation
- Intermediate data base holds current results of low-level vision
- Working memory with schema instances of varying confidence levels
- Long term memory holds world knowledge about schemas and their relationships

HEARSAY: Schemas for Speech Understanding

- A cooperative computation approach to perception
- Different hypotheses on different layers of the blackboard, and with time-varying confidence levels compete and cooperate to cover the speech stream
- The implementation was serial, but think of the architecture as distributed