Reverse Engineering the Human Visual System

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Reverse Engineering the Brain

What does that mean?

Building computational machines that are functionally equivalent to the brain

in their ability to perceive, think, decide, and act in a purposeful way to achieve goals in complex, uncertain, dynamic, and possibly hostile environments, despite unexpected events and unanticipated obstacles, while guided by internal values and rules of conduct.

Functional equivalence ::= producing the same input/output behavior

Reverse Engineering the Brain

Will require a deep understanding of how the brain works and what the brain does

How is information represented in the brain?

How is computation performed?

What are the functional operations?

What are the knowledge data structures?

How are messages encoded?

How are images processed?

How are relationships established and broken?

How are signals transformed into into symbols?

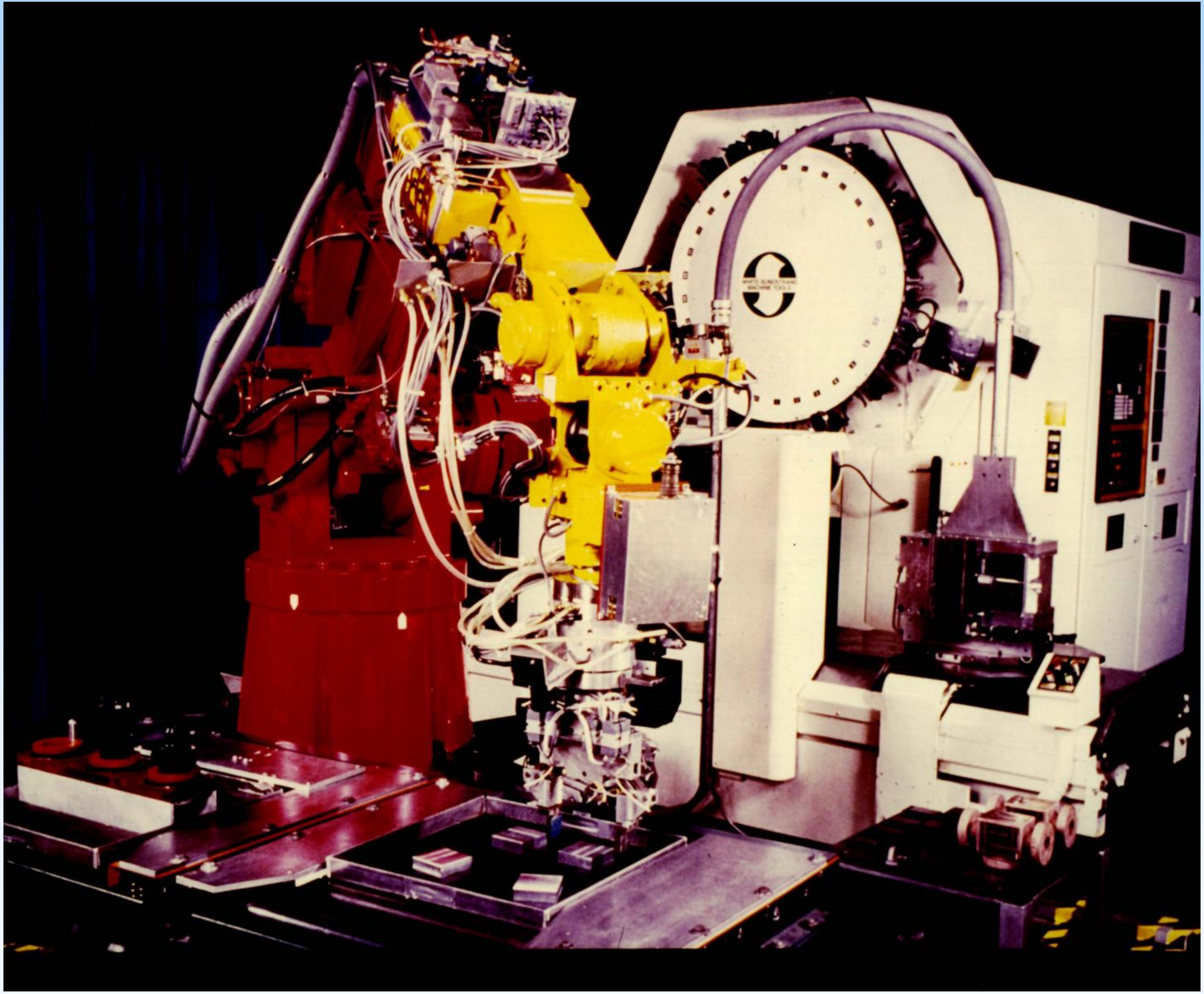
How does the brain generate the incredibly complex colorful, dynamic internal representation that we consciously perceive as external reality?

Engineering Intelligent Systems

Intelligent Control Projects ~ $100M total over 43 years

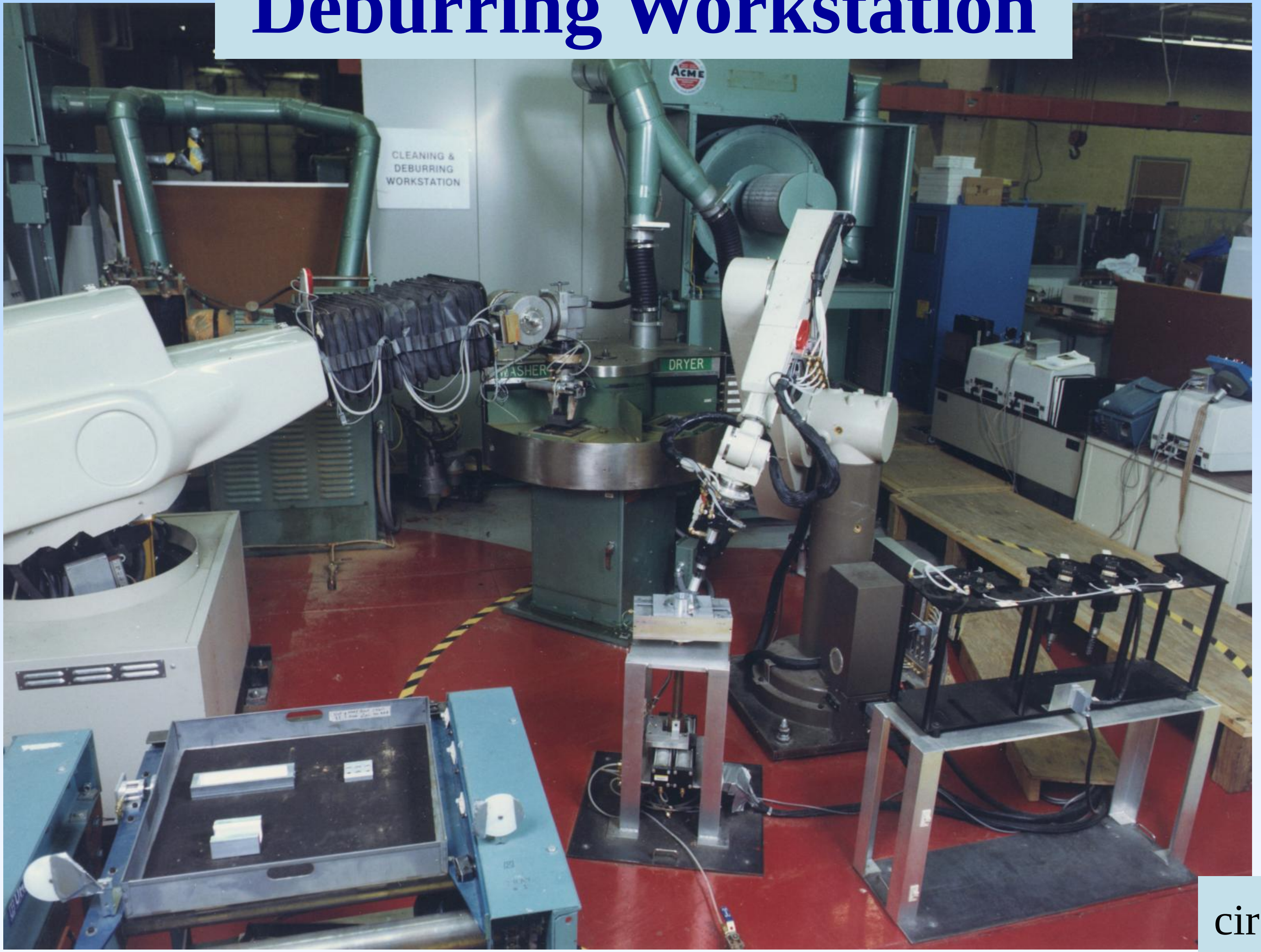
65-75 **NASA-NBS** -- Cerebellum model for learning control (CMAC neural net)
73-85 **Navy/NBS** – Robot control, Automated Manufacturing Research Facility
86-87 **DARPA** -- Multiple Unmanned Undersea Vehicles (MAUV)
88-89 **DARPA** -- Submarine Operational Automation System (SOAS)
90-92 **GD Electric Boat** -- Next generation nuclear submarine control
86-88 **NASA** -- Space Station Flight Telerobotic Servicer (NASREM)
87-89 **Bureau of Mines** -- Coal mine automation
87-91 **U.S. Postal Service** -- Stamp distribution center, General mail facility
86-08 **Army** -- TEAM, TMAP, MDARS, Picatinny Arsenal UGV, Demo I and III ARL Collaborative Technology Alliance, JAUGS, VTA, FCS-ANS
96-97 **Navy** – Double Hull Robot, Multiple UAV SWARM
94-95 **DARPA / General Motors** – Enhanced CNC & CMM Control
99-01 **Boeing** – Cell Control, Riveting, Hi Speed machine tool
92-01 **Commercial CNC** - plasma & water jet cutting
96-98 **DARPA** – MARS, PerceptOR
02-04 **Boeing/SAIC** – FCS Autonomous Navigation System, Integrated Combat Demo
02-07 **AirForce** – RoboCrane Paint Stripping Robot for Large Aircraft
08-09 **DOT** – Intelligent vehicles, Foveal-Peripheral Vision for Driving
06-07 **DARPA** – Learning Applied to Ground Robotics (LAGR)
08-10 **DARPA** – EATR Foraging Robot

Intelligent Machining Workstation



circa 1981

Intelligent Cleaning and Deburring Workstation



circa 1982

Intelligent Coal Mining Machine

circa 1988

Multiple Autonomous Undersea Vehicles

circa 1989

Intelligent Vehicle Control

circa 1993

NIST Autonomous Mobility Team

Intelligent Control for ARL Demo III Experimental Unmanned Vehicle

circa 1998

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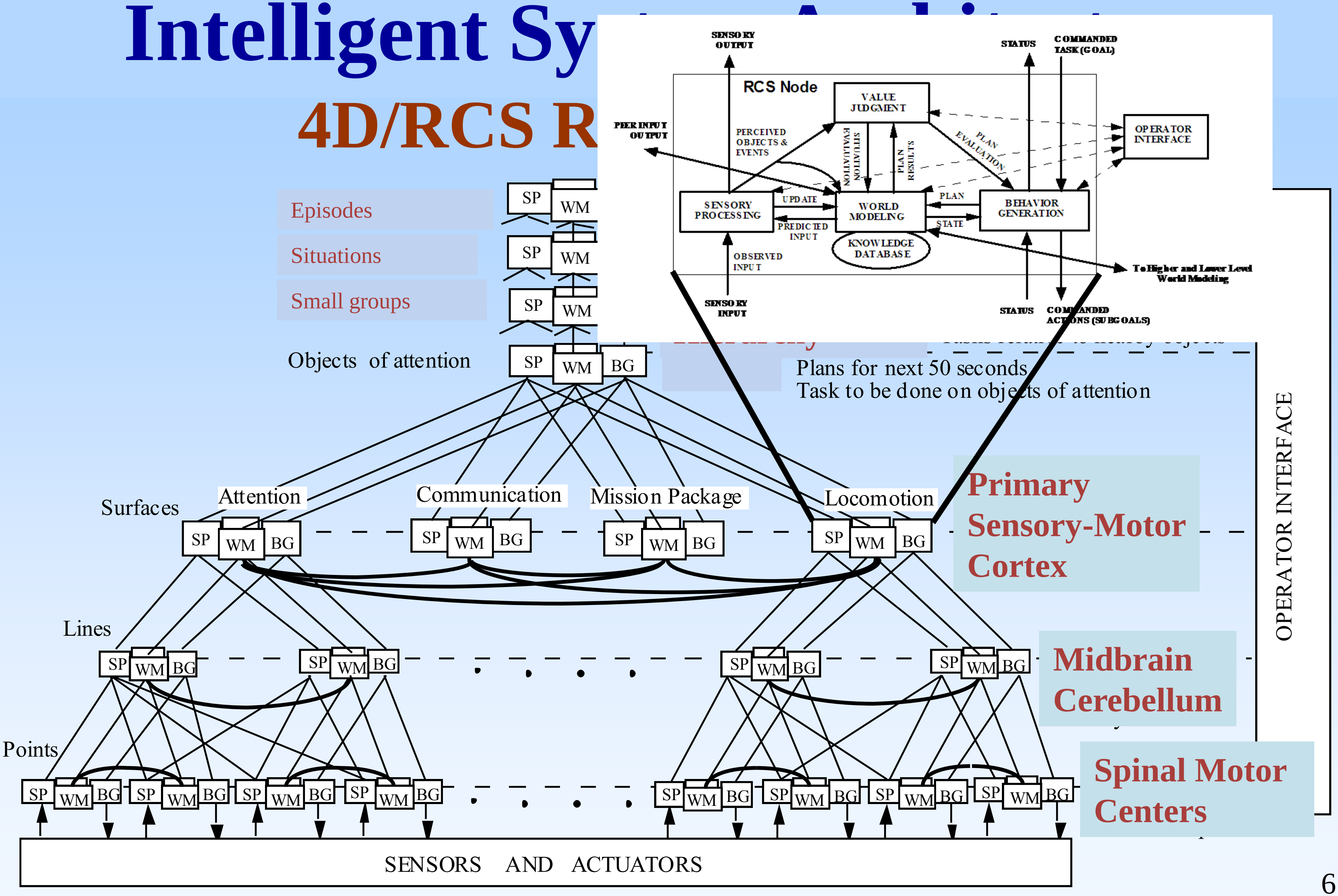
4D/RCS Reference Model Architecture for Unmanned Vehicle Systems

Adopted by GDRS for FCS Autonomous Navigation System
Adopted by TARDEC for Vetronics Technology Integration

- Hierarchical structure of goals and commands
- Representation of the world at many levels
- Planning, replanning, and reacting at many levels
- Integration of many sensors stereo CCD & FLIR, LADAR, radar, inertial, acoustic, GPS, internal

Intelligent Sy

4D/RCS R



Plans for next 50 seconds
Task to be done on objects of attention

Primary Sensory-Motor Cortex

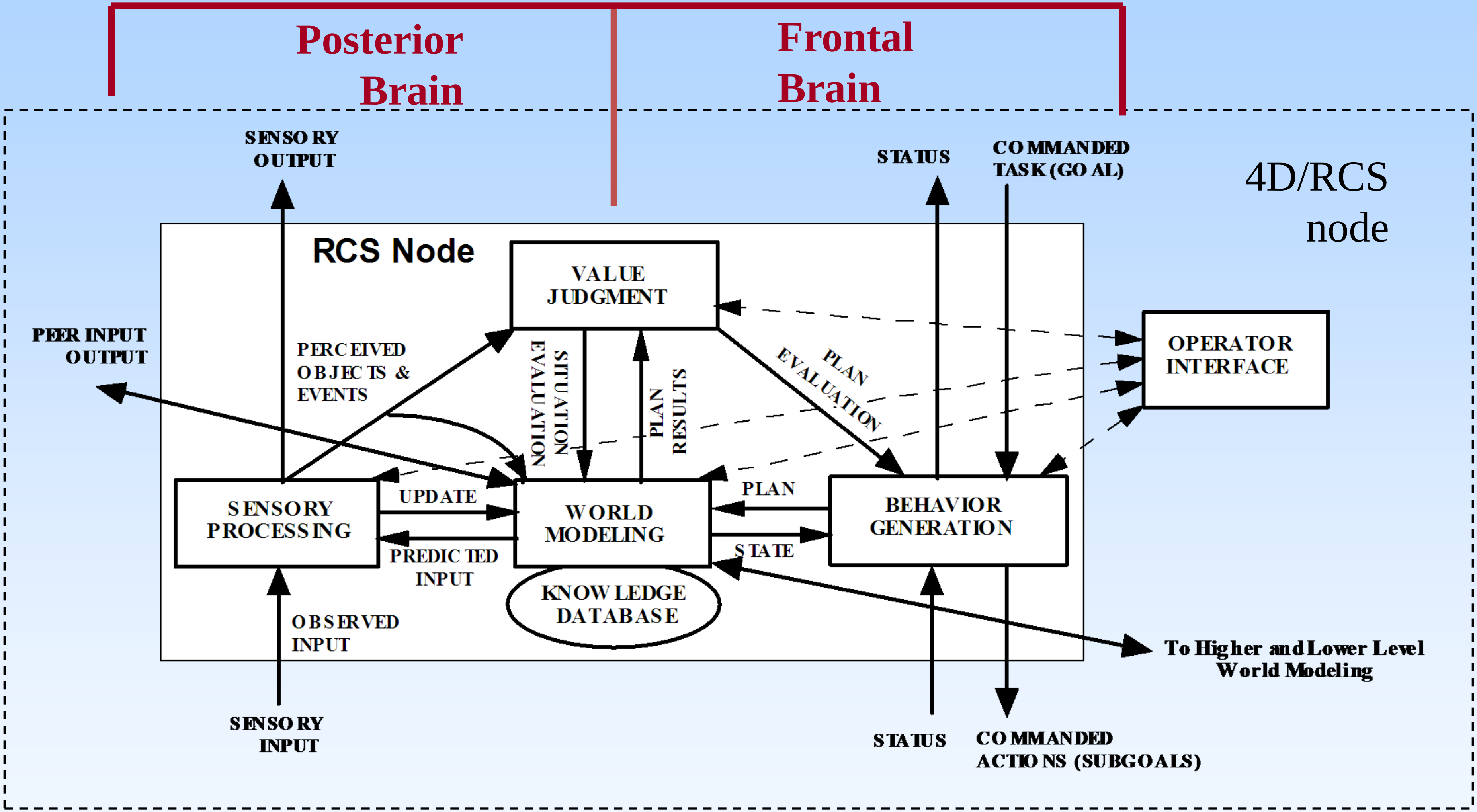
Midbrain Cerebellum

Spinal Motor Centers

Technology Maturity for Adaptive Massively Parallel Computing

A 4D/RCS Computational Node

Mapping to the Brain

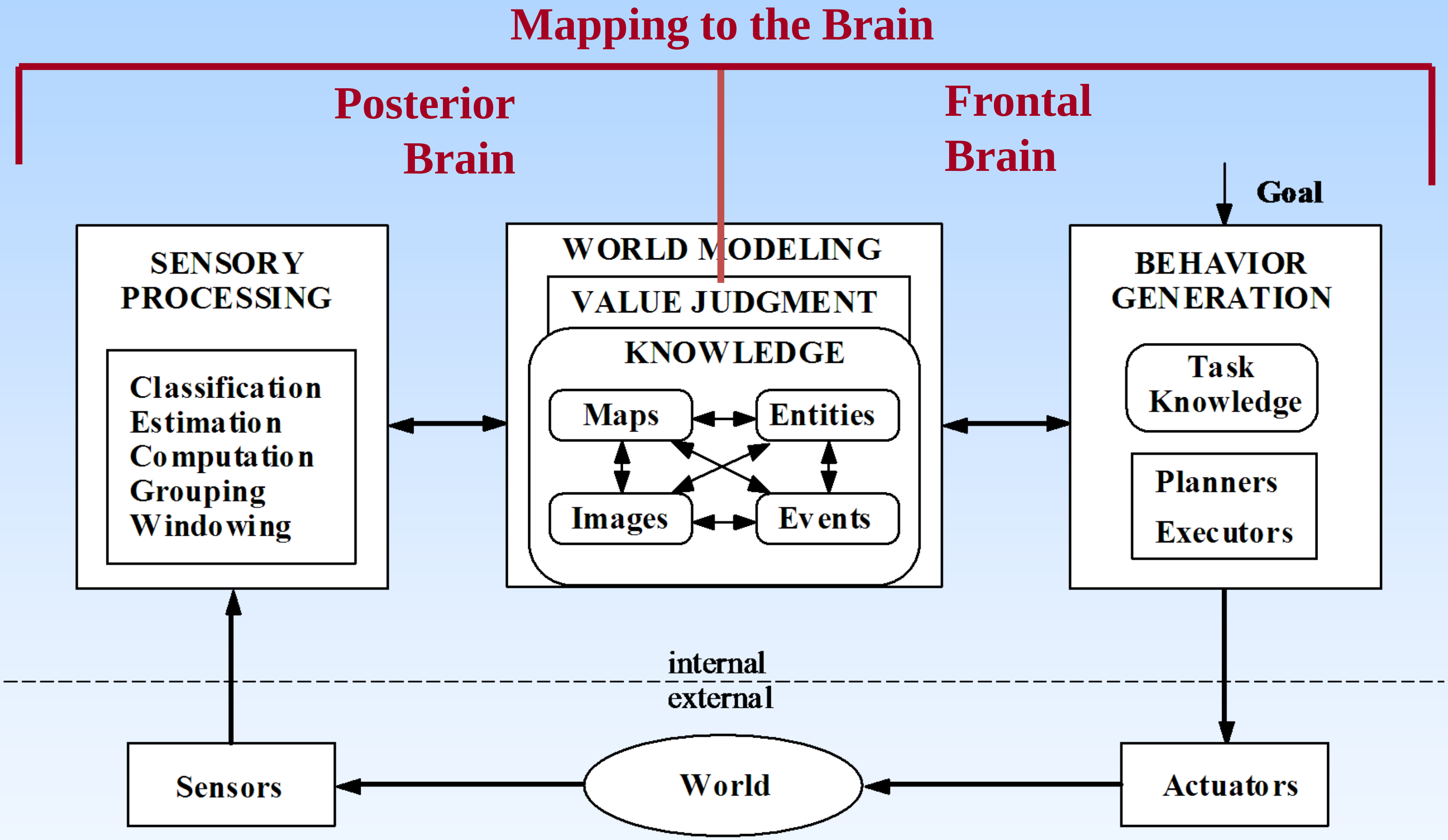


Posterior Brain

Frontal Brain

4D/RCS node

Functional Capabilities



Computational Architecture of Brain

What is the brain for?

The brain is first and foremost a control system

All brains generate and control behavior

Brains initially evolved to control locomotion

Evolution

- Swimming motion & gait generation – coordination of actuators
- Path planning – how to get from A to B
- Decision making – where to go, when, why, how
- Tactical behaviors – hunting for food, evading predators, . . .
- Strategic behaviors – migrating, establishing territory, mating, . . .

**Manipulation, language, and reasoning
are recent developments**

Hierarchical Architecture

Brain is organized hierarchically

Unitary SELF at top
Millions of sensors and actuators at bottom

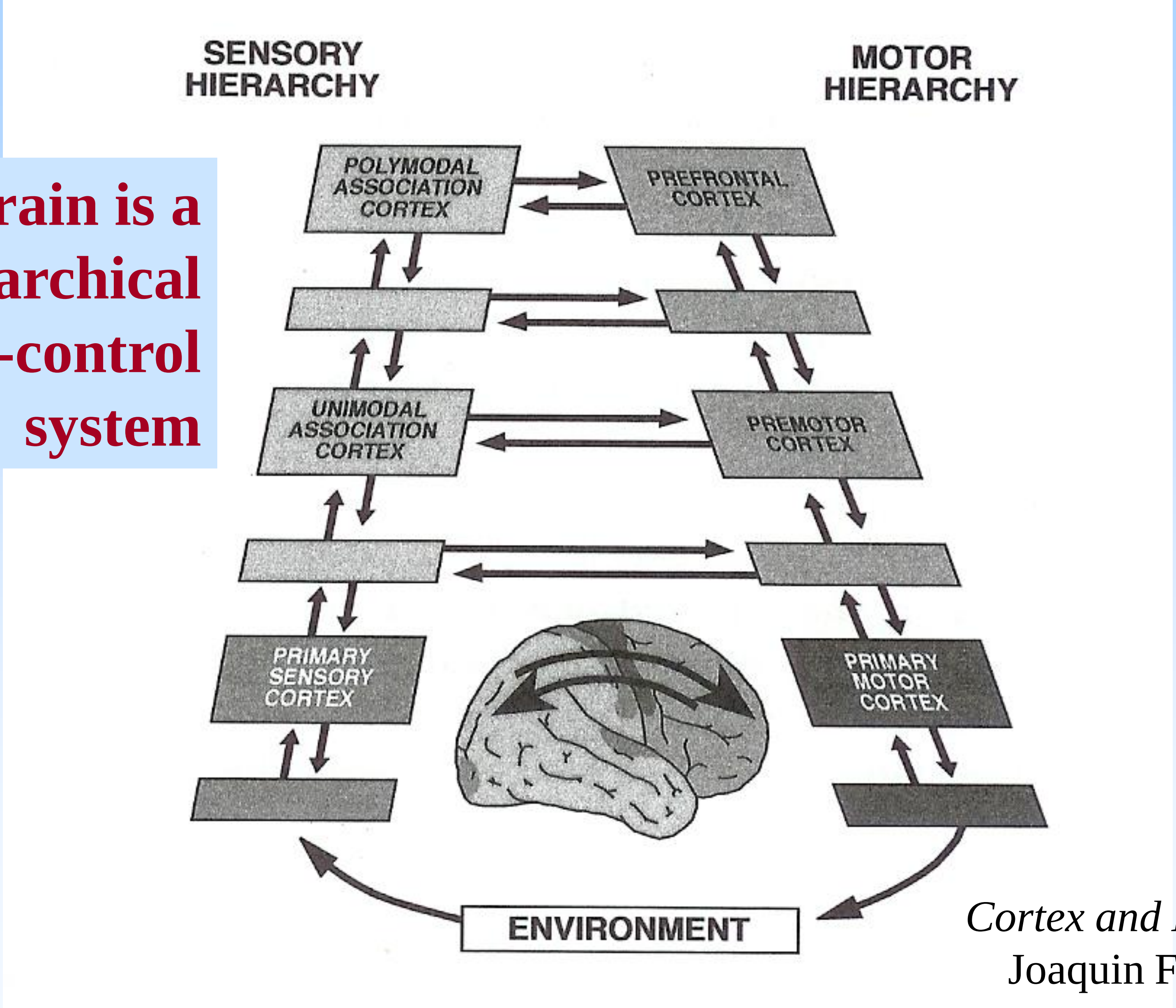
Complex strategies at top
Simple actions at bottom

Frontal hierarchy: **decision making, task decomposition, planning and execution of behavior**

Posterior hierarchy: **attention, segmentation, grouping, computation of attributes, filtering, and classification**

Cortical Architecture

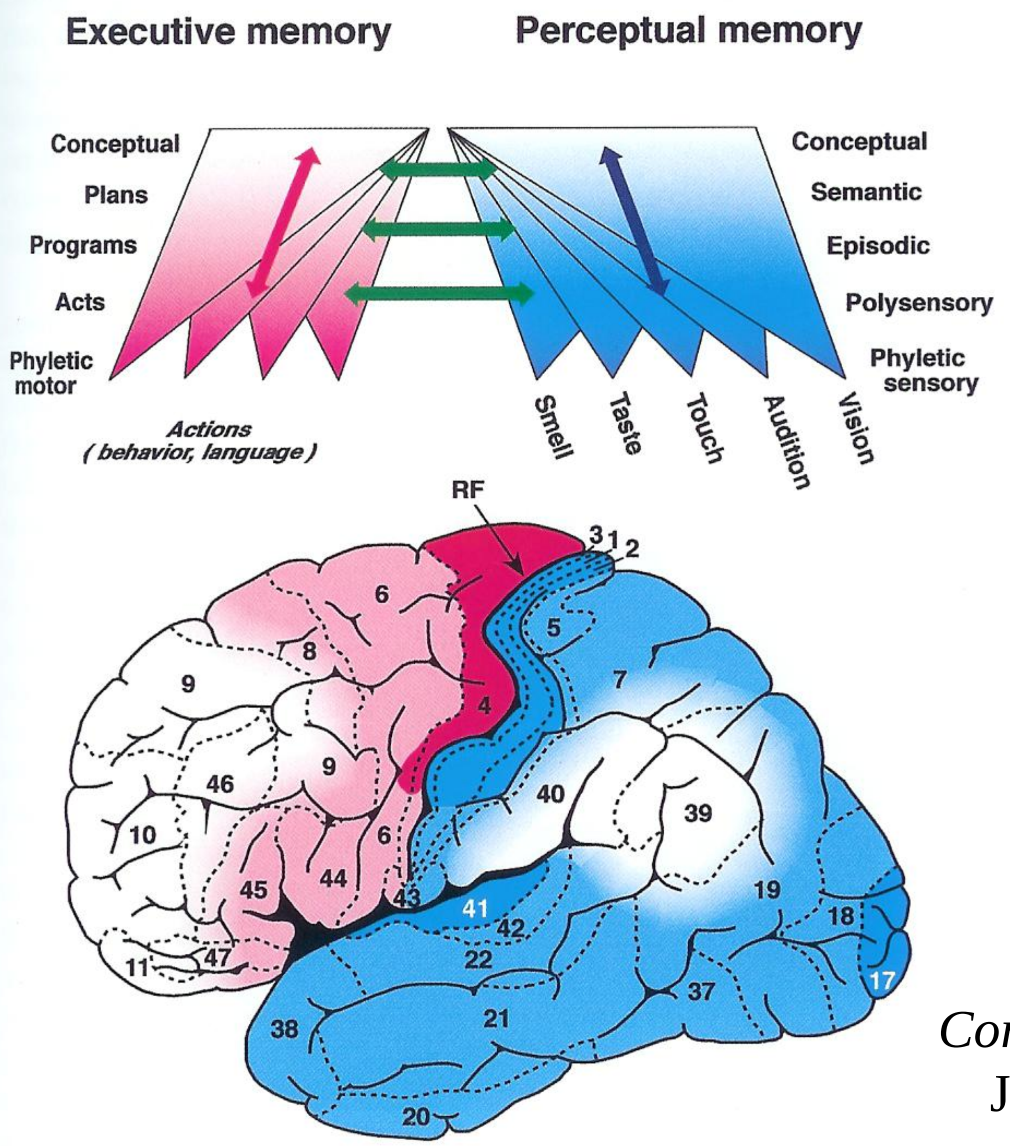
The brain is a hierarchical sensory-control system



Cortex and Mind
Joaquin Fuster

Hierarchical Architecture

More neurons at the top of the hierarchy



Cortex and Mind
Joaquin Fuster

Computational Mechanisms

Synapse is an electronic gate

-- complex biochemistry, site of long-term memory

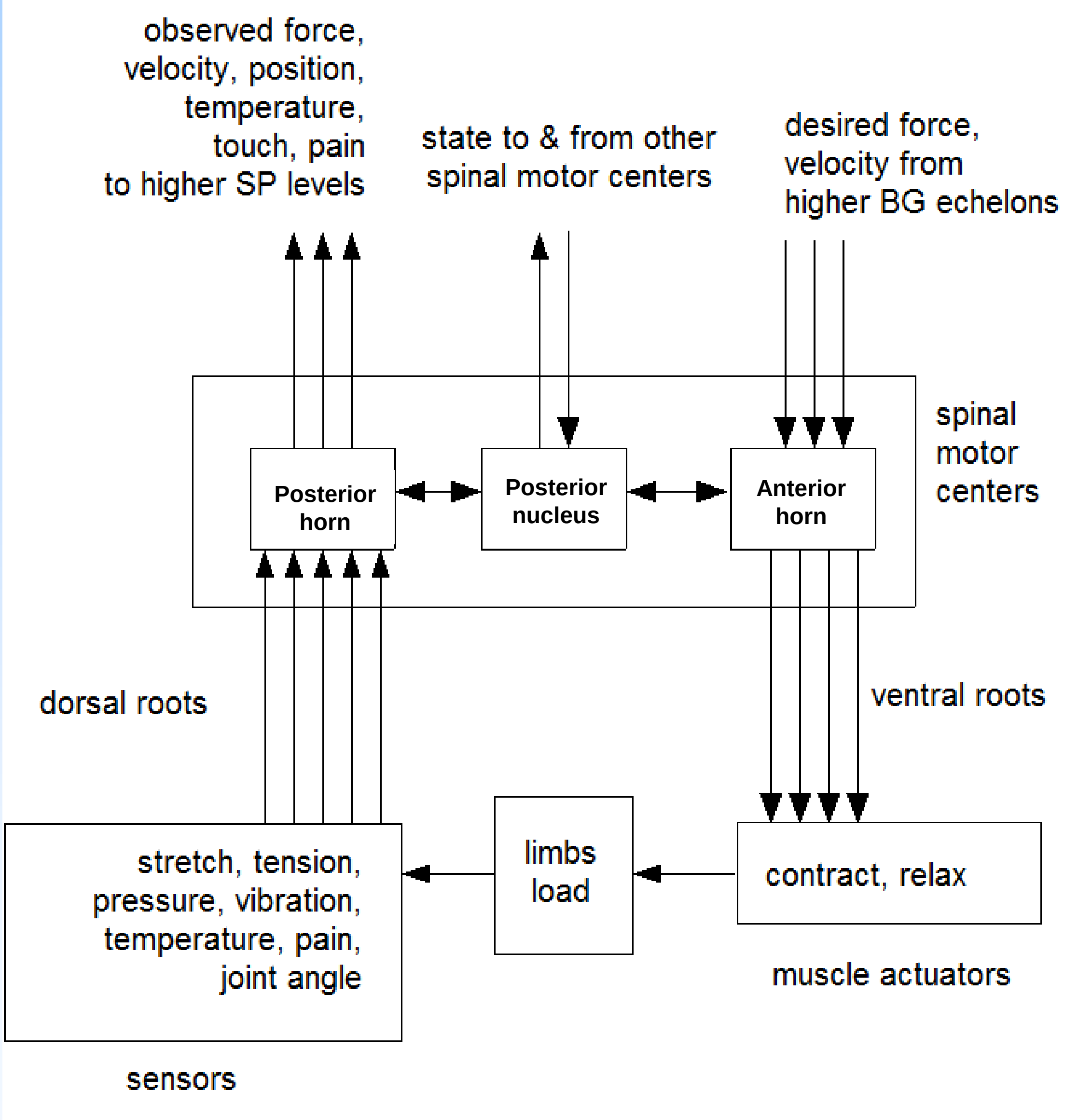
Neuron is a computational element

-- summation of many non-linear processes

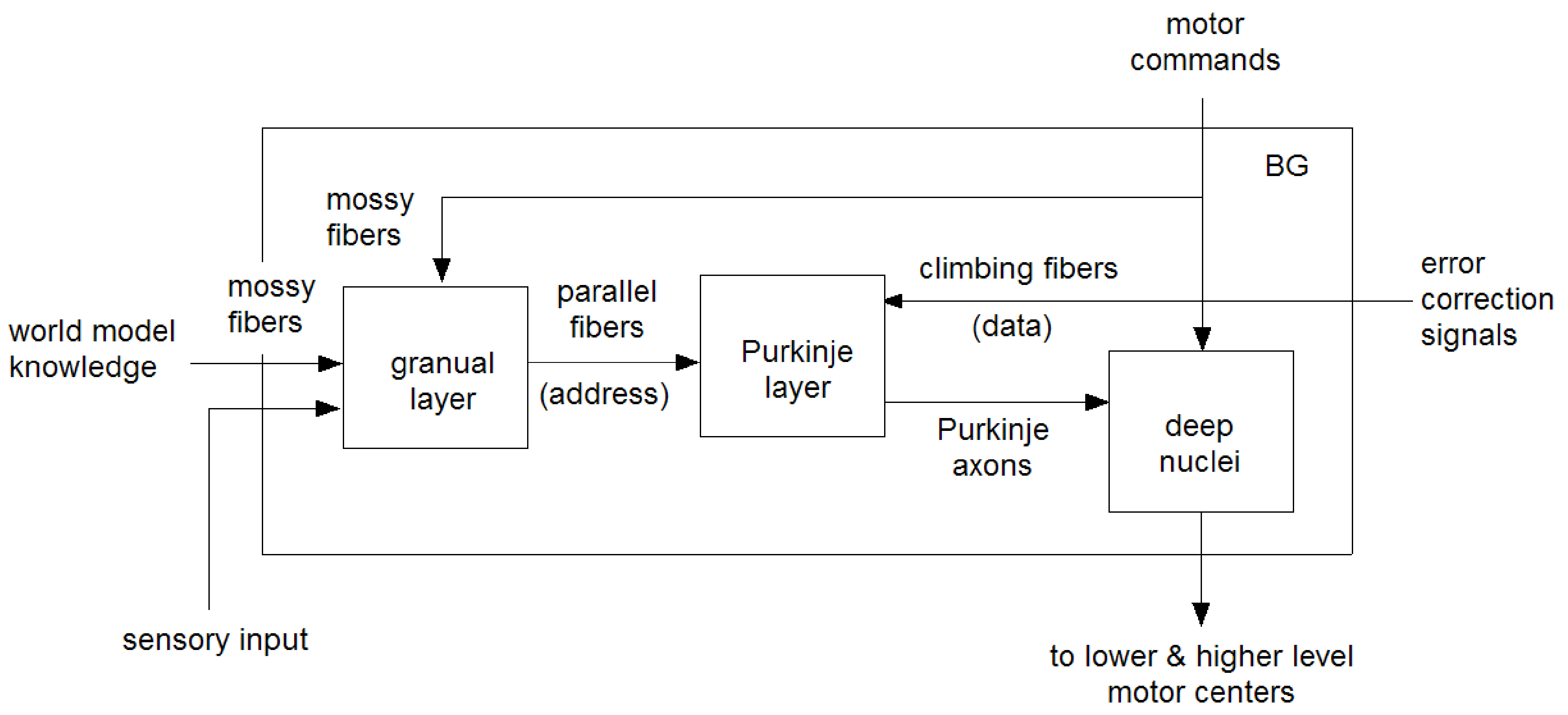
Neural Cluster is a functional unit

-- arithmetic or logical operations, correlation,
-- coordinate transformation, finite-state automata,
-- rules, grammar, direct and indirect addressing

Neural Clusters in Spinal Cord

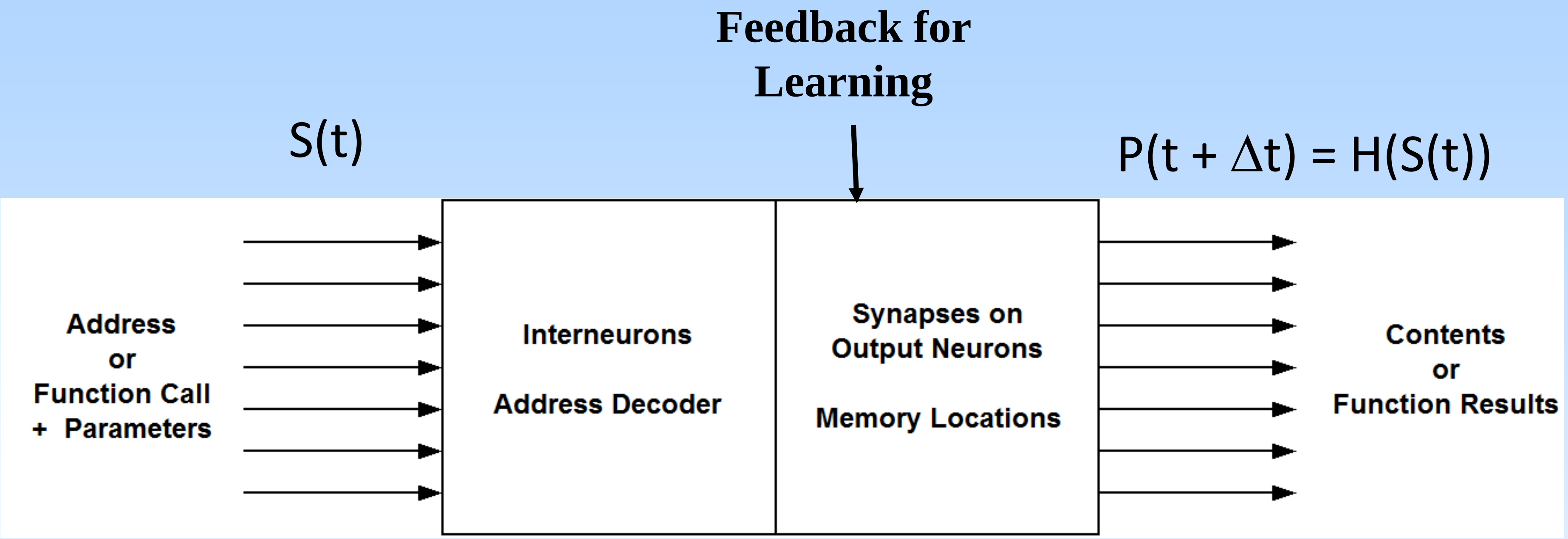


Neural Clusters in Midbrain (e.g. Cerebellum)



Marr 1969, Albus 1971

General Functional Model



Input vector or array

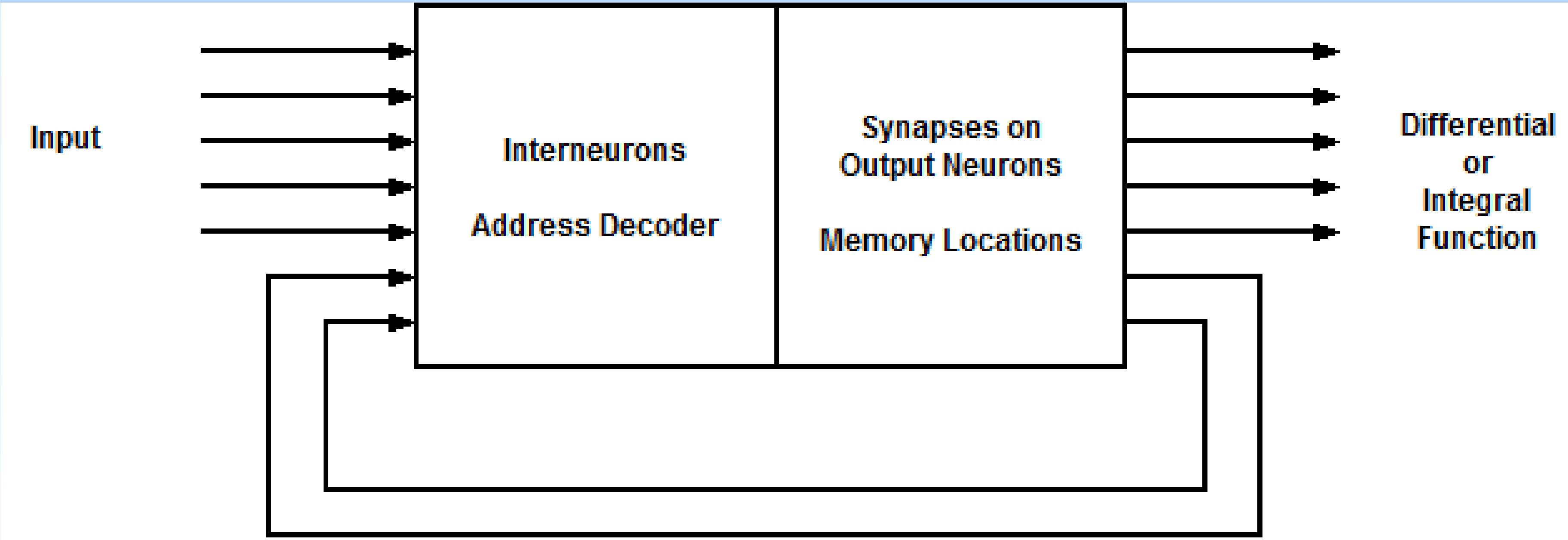
Output vector or array

memory recall, arithmetic or logical functions,
IF/THEN rules, goal-seeking reactive control,
forward & inverse kinematics, direct & indirect addressing

Functional Model + Feedback

S(t)

P(t + Δt) = H(S(t))

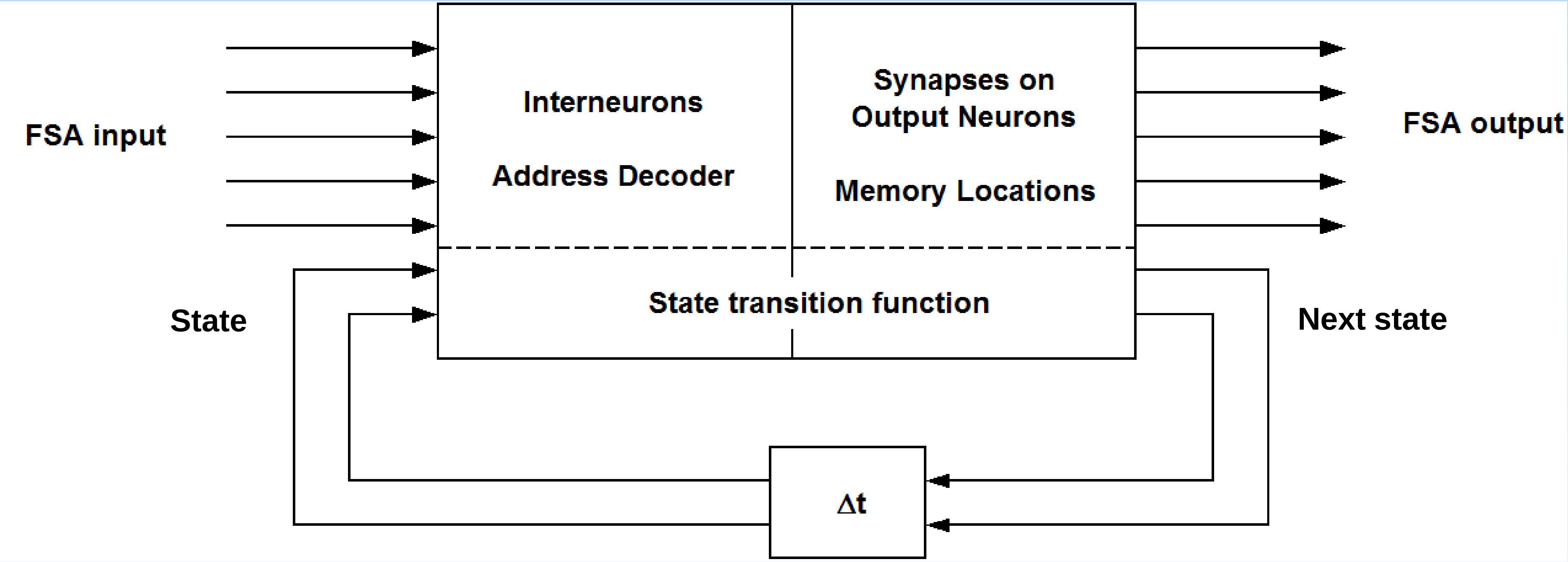


differential and integral functions, dynamic models, time and frequency analysis, phase-lock loops

A Neural Finite State Automaton

S(t)

$P(t + \Delta t) = H(S(t))$



Markov processes, scripts, plans, behaviors, grammars

Computation in Cortex

Microcolumn

100 – 250 neurons

30 – 50 μ diameter, 3000 μ long

-- pattern detector & attribute filter

Hypercolumn (a.k.a. column)

100+ microcolumns in a bundle

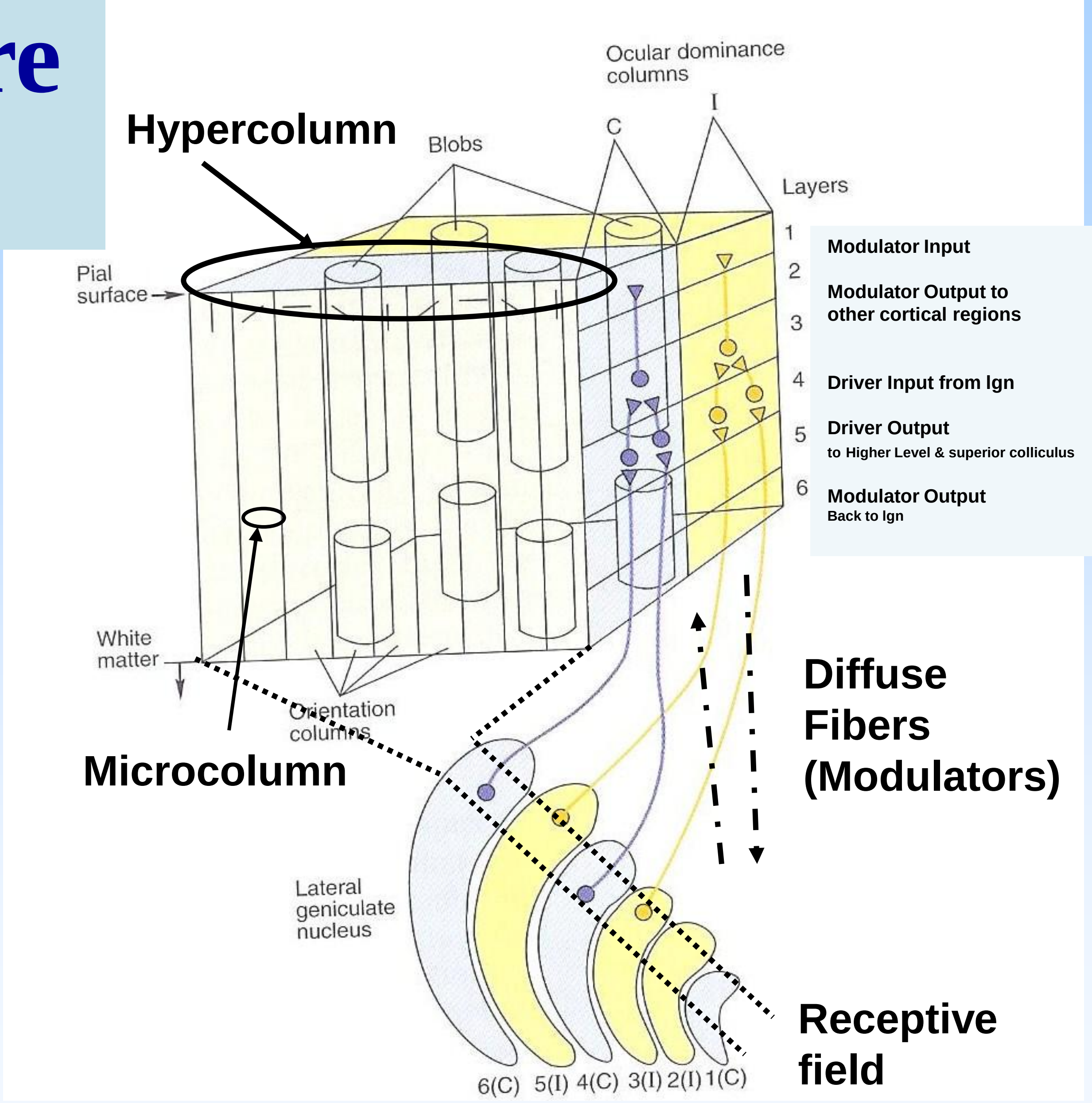
500 μ in diameter, 3000 μ long

-- computer, program library, & data structure

There are about 10^6 hypercolumns in human cortex

Architecture of Vision

Cortical Columns in V1 + Lateral Geniculate in Thalamus



Hypercolumn

Microcolumn

Modulator Input

Modulator Output to other cortical regions

Driver Input from lgn

Driver Output
to Higher Level & superior colliculus

Modulator Output
Back to lgn

Diffuse Fibers (Modulators)

Receptive field

Communication in the Brain

Axon is an active fiber connecting one neuron to others

(transmits a scalar variable on a
publish-subscribe network with bandwidth ~ 500 Hz)

Two kinds of axons:

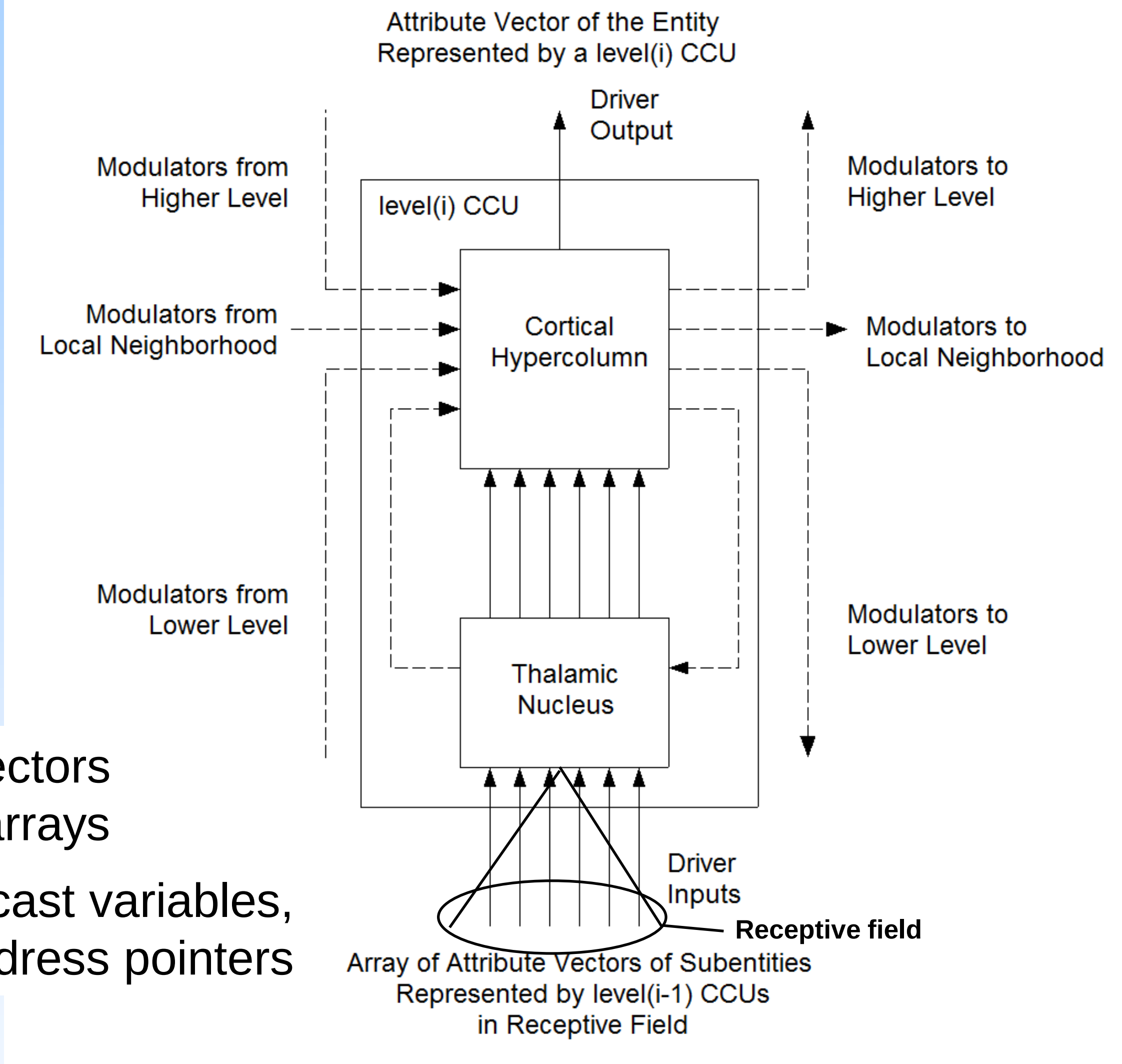
- **Drivers** – Preserve topology and local sign
  Arrays of attributes and state-variables
  e.g., convey color, shape, size, position, orientation, motion

- **Modulators** – Don't preserve topology or local sign
  Parameters, context, coefficients, addresses & pointers
  e.g., select & modify algorithms, establish relationships

Exploring the Thalamus
Sherman & Guillery 2006

Cortical Hypercolumn + Thalamic loop

Cortical Computational Unit (CCU)



Attribute Vector of the Entity
Represented by a level(i) CCU

Driver
Output

Modulators from
Higher Level

Modulators to
Higher Level

level(i) CCU

Modulators from
Local Neighborhood

Cortical
Hypercolumn

Modulators to
Local Neighborhood

Modulators from
Lower Level

Modulators to
Lower Level

Thalamic
Nucleus

Driver
Inputs

Receptive field

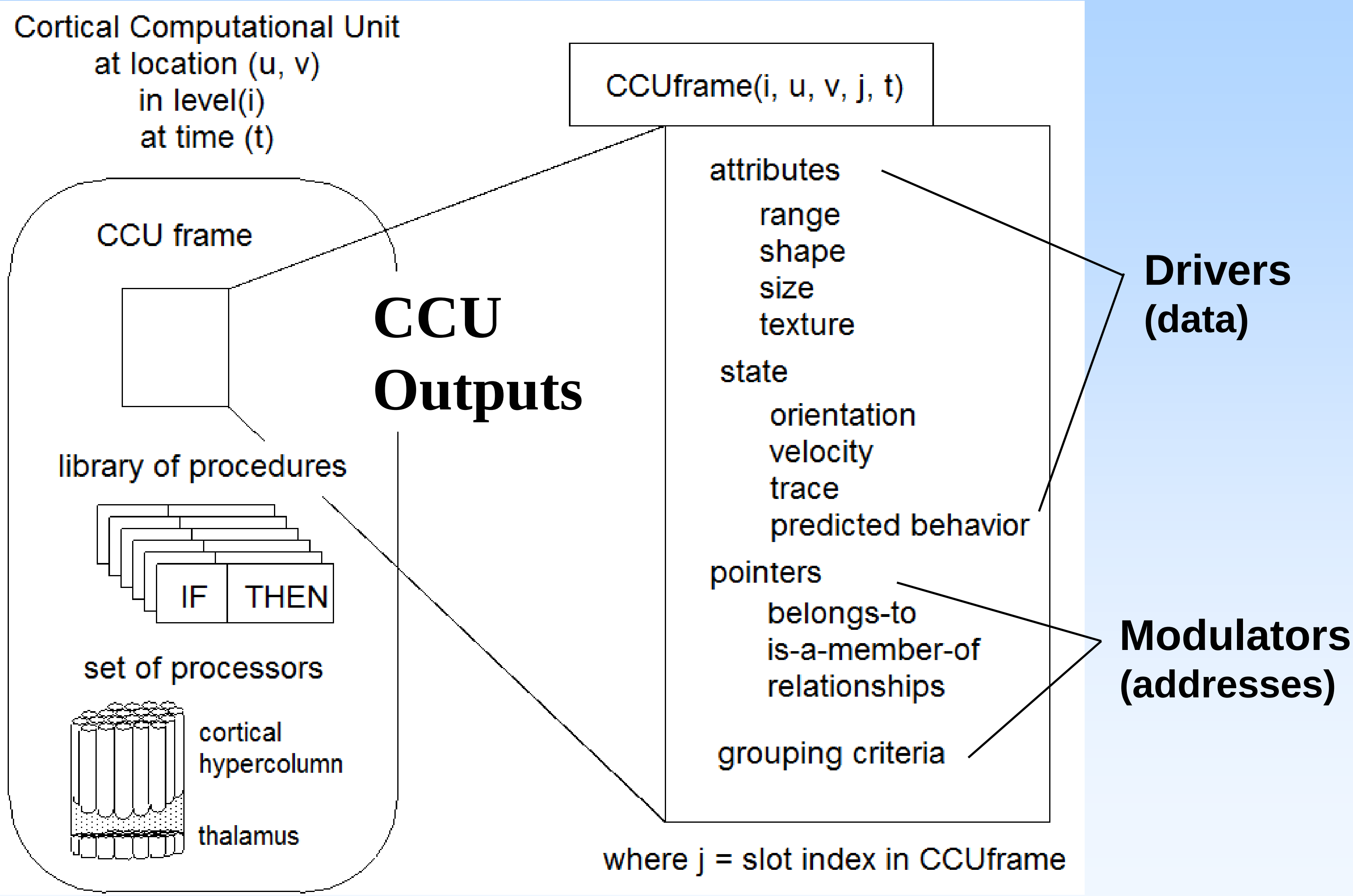
Array of Attribute Vectors of Subentities
Represented by level(i-1) CCUs
in Receptive Field

——→ drivers = attribute vectors & arrays

- - - - → modulators = broadcast variables, & address pointers

windowing, segmentation, grouping, computing group attributes & state, filtering, classification, setting and breaking relationships

CCU Data Structure Hypothesis



Cortical Computational Unit
at location (u, v)
in level(i)
at time (t)

CCU frame

library of procedures

IF THEN

set of processors

cortical hypercolumn

thalamus

CCU Outputs

CCUframe(i, u, v, j, t)

attributes
- range
- shape
- size
- texture

state
- orientation
- velocity
- trace
- predicted behavior

pointers
- belongs-to
- is-a-member-of
- relationships

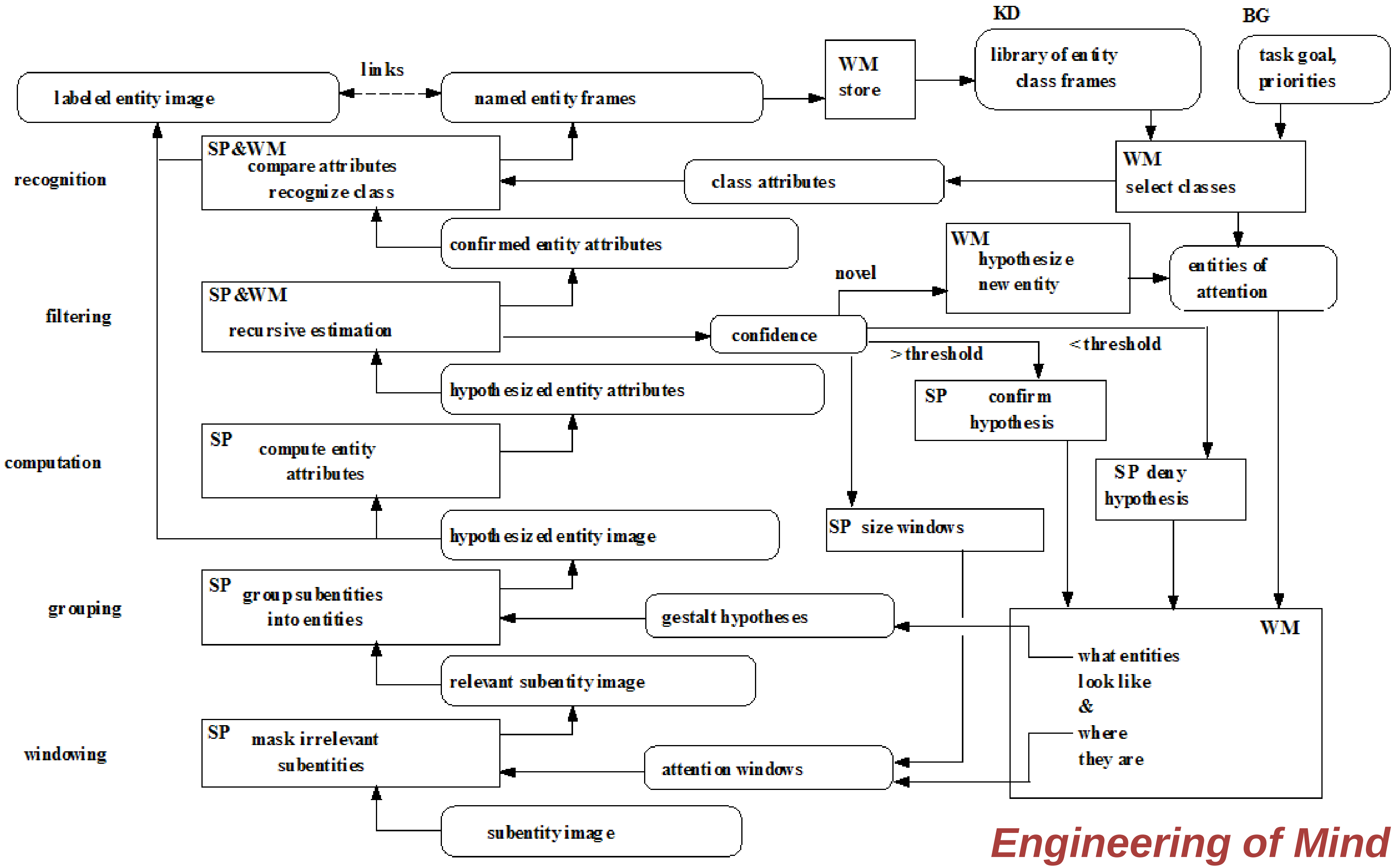
grouping criteria

Drivers (data)

Modulators (addresses)

where j = slot index in CCUframe

CCU Computational Model for Vision



KD

BG

labeled entity image

links

named entity frames

WM store

library of entity class frames

task goal, priorities

recognition

SP&WM compare attributes recognize class

class attributes

WM select classes

confirmed entity attributes

novel

WM hypothesize new entity

entities of attention

filtering

SP &WM recursive estimation

confidence

>threshold

<threshold

hypothesized entity attributes

SP confirm hypothesis

computation

SP compute entity attributes

SP deny hypothesis

hypothesized entity image

SP size windows

grouping

SP group subentities into entities

gestalt hypotheses

WM

what entities look like & where they are

relevant subentity image

windowing

SP mask irrelevant subentities

attention windows

subentity image

Engineering of Mind

Albus & Meystel 2001

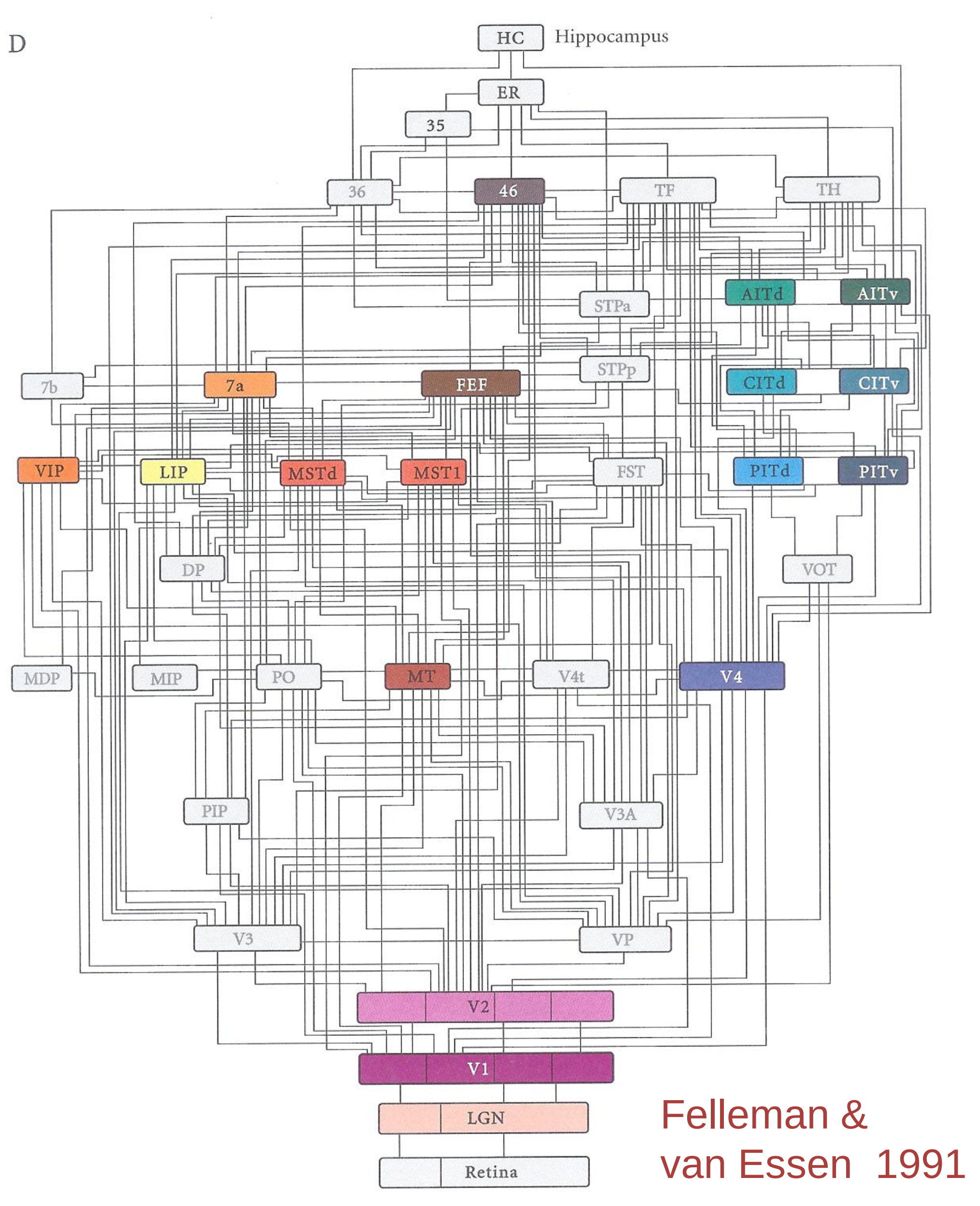
Circuit diagram of visual system in brain

12 layers

32 areas

Each area is an array of Cortical Columns

Each area represents the Visual Field of Regard

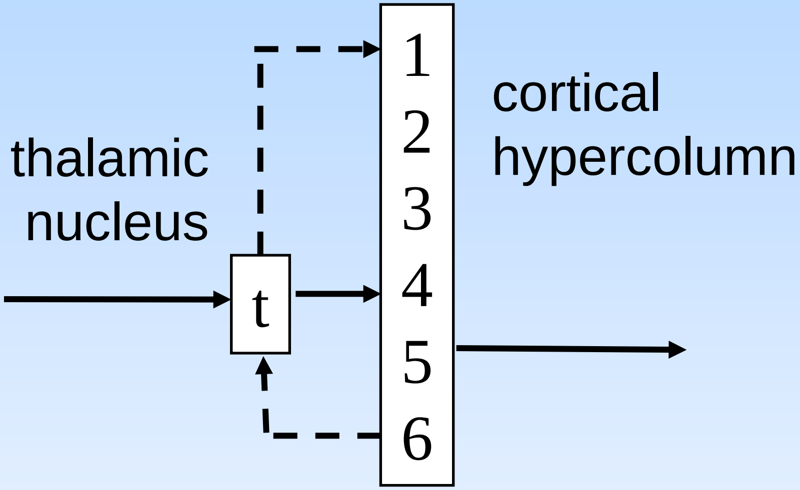


Felleman & van Essen 1991

Cortico-Thalamic Loop

⟶ drivers = attribute vector array

⇢ modulators = address pointers

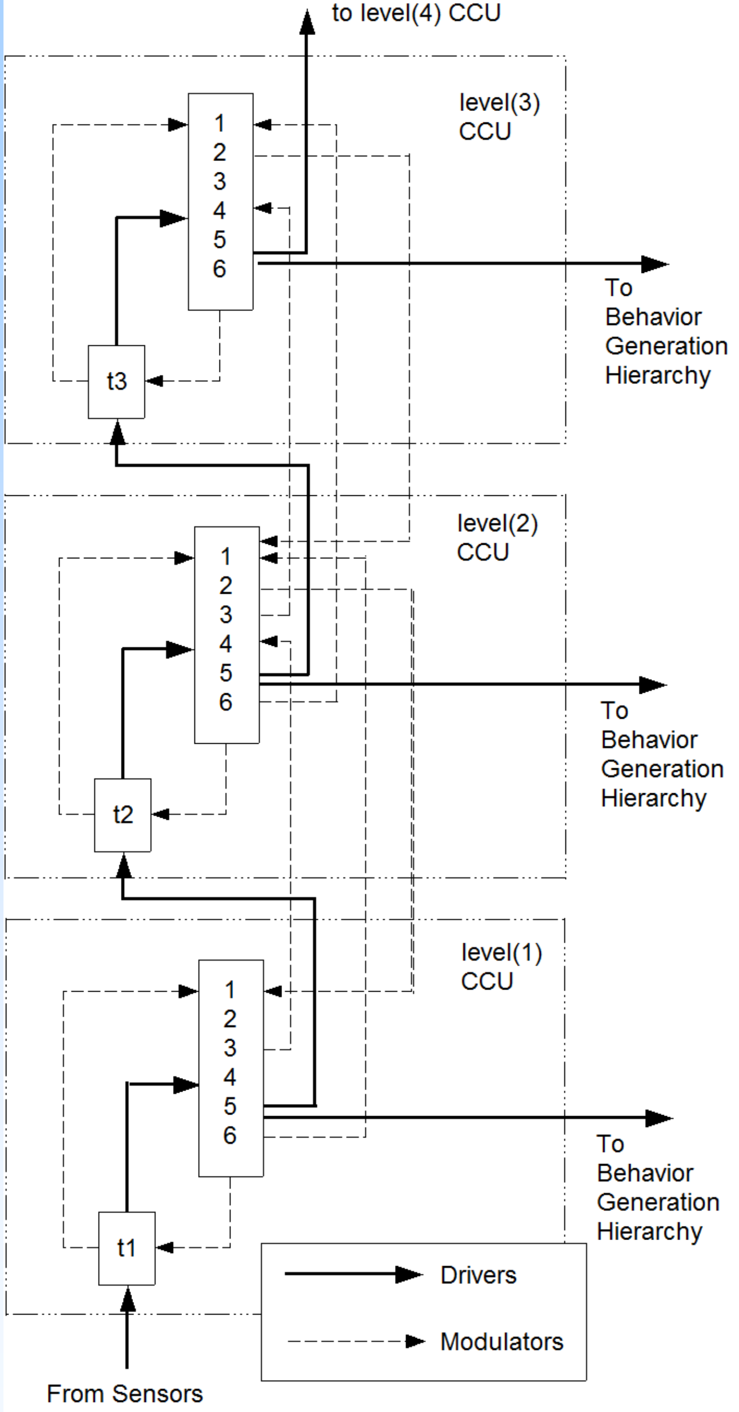


A Cortical Computational Unit (CCU)

windowing
segmentation & grouping
compute group attributes
recursive filtering
classification
setting/breaking pointers

Cortico-Thalamic Loop Hierarchy

windowing
segmentation & grouping
compute group attributes
recursive filtering
classification
setting/breaking pointers
at each level



Two types of hierarchies

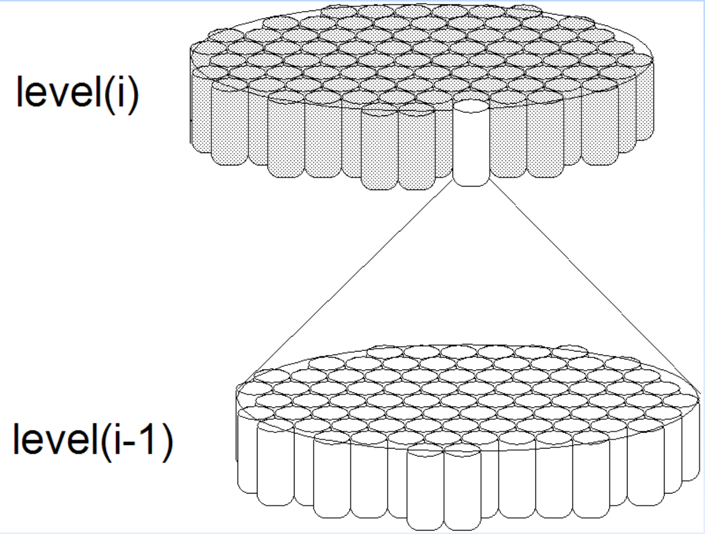
1. **Receptive field hierarchies**

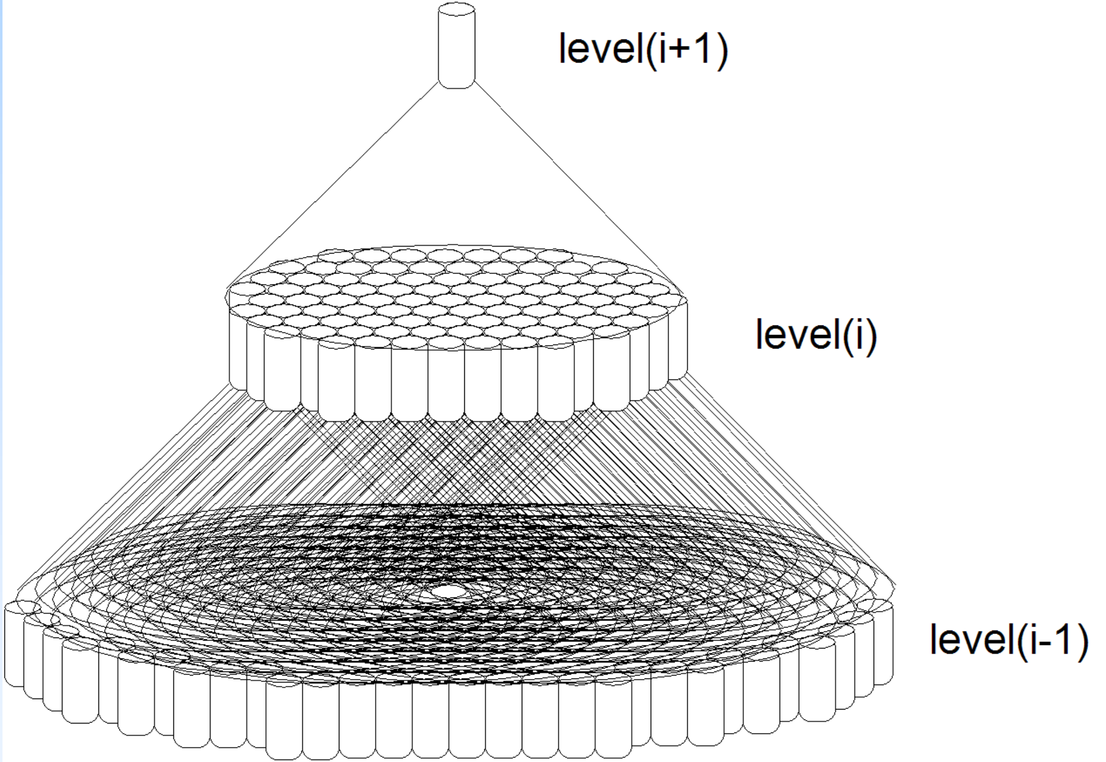
   Are defined by driver anatomical connectivity and are relatively fixed

2. **Entity and Event hierarchies**

   Are defined by *belongs-to* and *has-part* pointers that can be established or broken in ~ 10 ms

CCU Receptive Field Hierarchy





Defined by driver neurons flowing up the processing hierarchy

CCU Entity/Event Hierarchy

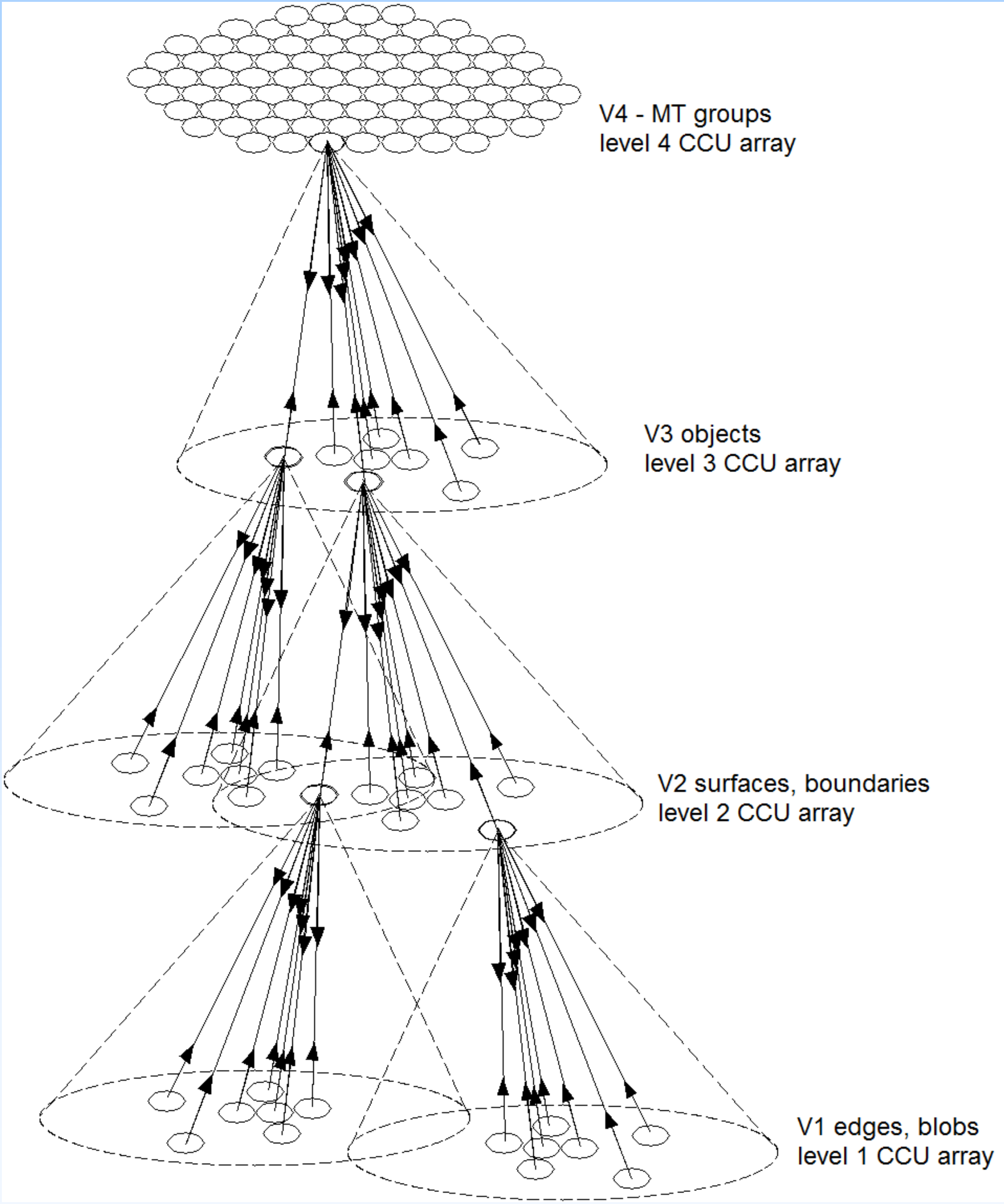
Defined by pointers

set by spatial/temporal grouping processes

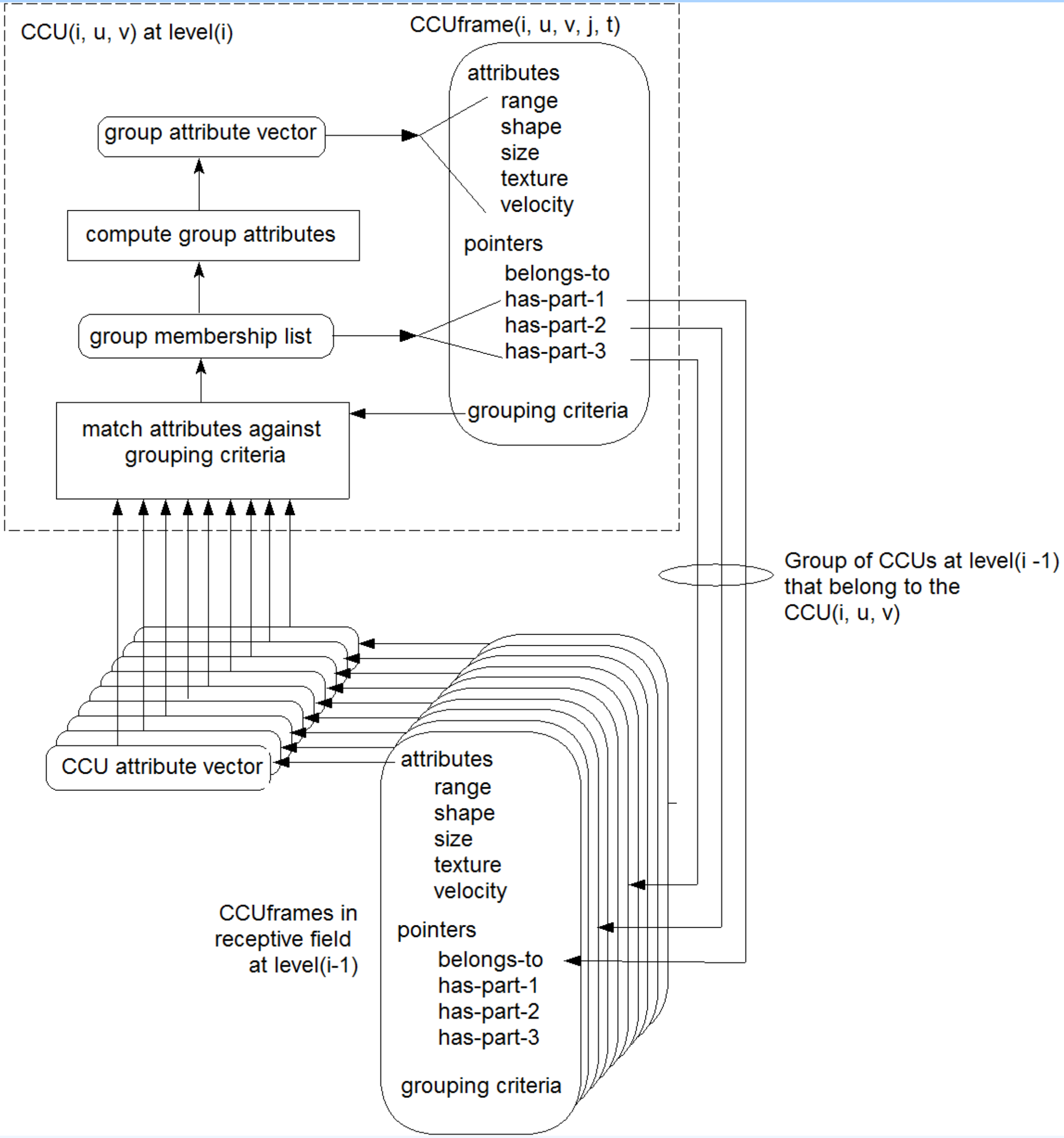
Pointers link pixels to symbols & vice versa

Provides symbol grounding

Pointers reset top to bottom within a saccade ~ 150 ms



Segmentation & Grouping Process



Each level detects patterns within its receptive field in the level below & sets and breaks pointers

This produces an Entity/Event Hierarchy

What is the path to success for reverse engineering the brain?

Pick the right level of resolution

- **overall system level** (central nervous system)

AI and Cognitive Neuroscience

- **arrays of macro-computational units** (e.g., cortical regions)
- **macro-computational units** (e.g., cortical hypercolumns & loops)

CCUs

- **micro-computational units** (e.g., cortical microcolumns & loops)
- **neural clusters** (e.g., spinal and midbrain sensory-motor nuclei)
- **neurons** (elemental computational units) – input/output functions

Mainstream Neuroscience & Neural Nets

- **synapses** (electronic gates, memory elements) – synaptic phenomena
- **membrane mechanics** (ion channel activity) – molecular phenomena

Pick the right level of resolution

There are 10^6 CCUs in the human cortex
(~ ¼ related to visual perception)

Real-time modeling ~ 20 cycles per second

=> ~ 10^7 CCU modeling cycles/sec

Real-time modeling at level of CCU seems within current technology

Computational Estimates for whole brain at CCU level

State of art supercomputer 10^{15} fops

Allocating this to 10^{6} CCUs running at 20 Hz yields 50 million fops per CCU per cycle

Estimated communication load between CCUs

10^{6} bytes per second for each CCU, or
10^{12} bps for full brain model

This appears to be within the state of the art for current supercomputers

Summary & Conclusions

- Cortical Computational Unit (CCU) is a computational module in cortex
- Each CCU consists of
  - -- a data frame with attributes and pointers
  - -- computational processes to maintain it
- Reverse engineering the brain requires selecting the right level of resolution, e.g. CCU level of resolution
- Real-time modeling at CCU level of resolution appears feasible *now* with current supercomputers
  -- maybe in < 20 years with PC computers

Thank you

What are the Inputs?

Gravity sensors establish the horizontal plane for an internal egosphere representation

Body kinematics measured by proprioception

Body dynamics measured by vestibular sensors

Tactile input <= Arrays of sensors in the skin

Visual input <= Arrays of sensors in the retina

Audio input <= Arrays of sensors in the ears

Smell and taste input <= Sensors in nose and mouth

What are the Outputs?

Behavior that is consistent with goals that are generated in the frontal cortex by processes that use:

- a rich internal model of the external world
- an internal representation of needs and desires

Behavior that consists of:

- control signals to muscles
- forces and velocities in the limbs and torso
- goal-driven tasks and subtasks on objects in the world

Behavior that has many levels of resolution in:

- planning and coordination
- feedback error correction
- feed-forward control

Overall Structure

Front to back:

Behavior generation in front
Sensory processing in back

Side to side:

Representation of right egosphere on left side
Representation of left egosphere on right side

Top to bottom:

Conscious self at top
Sensors and muscles at bottom

At the center:

Emotions: *good-bad, attractive-repulsive, cost-benefit, love-hate, fear-hope, confidence-uncertainty*
Appetites
Internal state

Morphology

Cortex is a 2D sheet – 2000 cm^2 in area x 3 mm thick

Cortical sheet is partitioned into functional regions

Regions are arranged in hierarchical layers

Each region is segmented into arrays of columns

Each column functions as a Cortical Computational Unit (CCU)*

CCUs have driver & modulator inputs & outputs

CCUs compute functional transformations, manage data structures, and establish links with other CCUs*

*** an engineering hypothesis**

Computational Mechanisms

Cortical Computational Unit (CCU) is a collection of functional units

– in posterior cortex capable of:

focus of attention, segmentation and grouping, calculation of group attributes and state, classification, and establishing relationships

– in frontal cortex capable of:

reasoning, decision making, goal selection, task decomposition, planning, and control

What is the path to success for reverse engineering the brain?

Pick the right level of resolution

There are 10^{11} neurons and 10^{15} synapses in the brain

Real-time modeling for neurons > 100 cycles/sec
for synapses > 1000 cycles/sec

Implies 10^{13} to 10^{18} modeling cycles/sec

Real-time modeling at level of synapse or individual neuron seems beyond current technology