UNIVERSITÀ
DEGLI STUDI
DI PADOVA

ARCHITECTURES FOR ROBOTS' AUTONOMY

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Intelligent Robotics Course

DIPARTIMENTO
DI INGEGNERIA
DELL'INFORMAZIONE

INTELLIGENT AUTONOMOUS SYSTEMS LAB

Recap: Where We've Been…

- **AI researchers** view robotics as an issue of *increasing autonomy* (doing the "right thing" in an open world),
- **Control engineers** view robotics as an issue of *extending automation* (focus on creating a closed world and guaranteeing actions).

This gives rise to very different, though not necessarily mutually exclusive, approaches especially in terms of programming.

The Big Picture

- AI has converged on a canonical software architecture after years of exploration
  - Historical development is of interest because it helps identify legacy code and see barriers that led to the convergence
- Software architectures have advantages
  - S/W engineering principles of abstraction, modularity
  - Semiformal design specification and completeness- master checklist, did you remember all the pieces
  - Can reveal (some) fundamental vulnerabilities

Organizing Software

- Overall style of design or organization is called an "**architecture**"
  - describes a set of architectural components and how they interact *[Dean & Wellman]*
  - provides a principled way of organizing a control system. However, in addition to providing structure, it imposes constraints on the way the control problem can be solved *[Mataric]*

Types of architectures

[Levis, George Mason University]

- **operational architecture:** describes ***what*** the systems does at a high level, not how it does it
- **systems architecture:** describes how a system works in terms of ***major subsystems***
- **technical architecture:** describes how a system works in terms of ***implementation details***, language

Types of architectures

Focus on theoretical and conceptual aspects…

- **operational architecture:** describes what the systems does, not how it does it
- **systems architecture:** describes how a system works in terms of major subsystems
- **technical architecture:** implementation details, language

…focus on implementation & software aspects.

Adapted from R.Murphy

Why Worry About Software Organization?

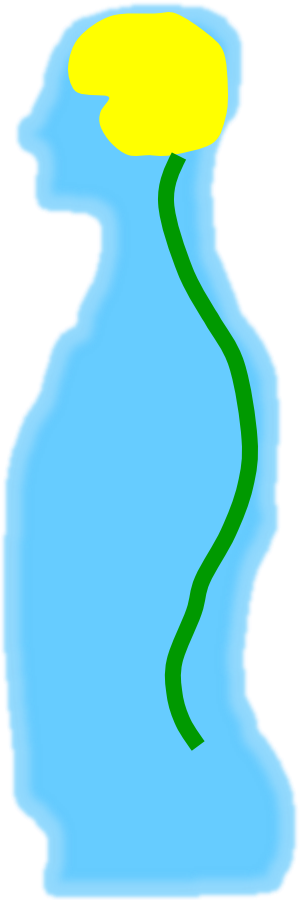
- Recall: at least **7 distinct areas of Artificial Intelligence in robotics:**
  - *knowledge reppresentation,*
  - *natural language,*
  - *learning,*
  - *planning and problem solving,*
  - *inference, search,*
  - *vision*

  each with own algorithms and data structures; these have to be "knitted" together somehow
- Software engineering is necessary for a successful software enterprise

Thinking About Architectures is Good Software Engineering

- **Abstraction**
  - Ignores details to permit focus for thinking about general organization of intelligence
  - Semiformal description
- **Modularity**
  - high cohesion (do one thing well, may be able to substitute different algorithms which produce same results “logical sensors”, “logical behaviours”, etc)
  - low coupling (which means may be able to add “apps”)
  - Supporting unit testing and debugging
- **Anticipation of change, Incrementality**
  - How to adapt, support evolution
- **Generality**
  - Not re-invent the wheel each time

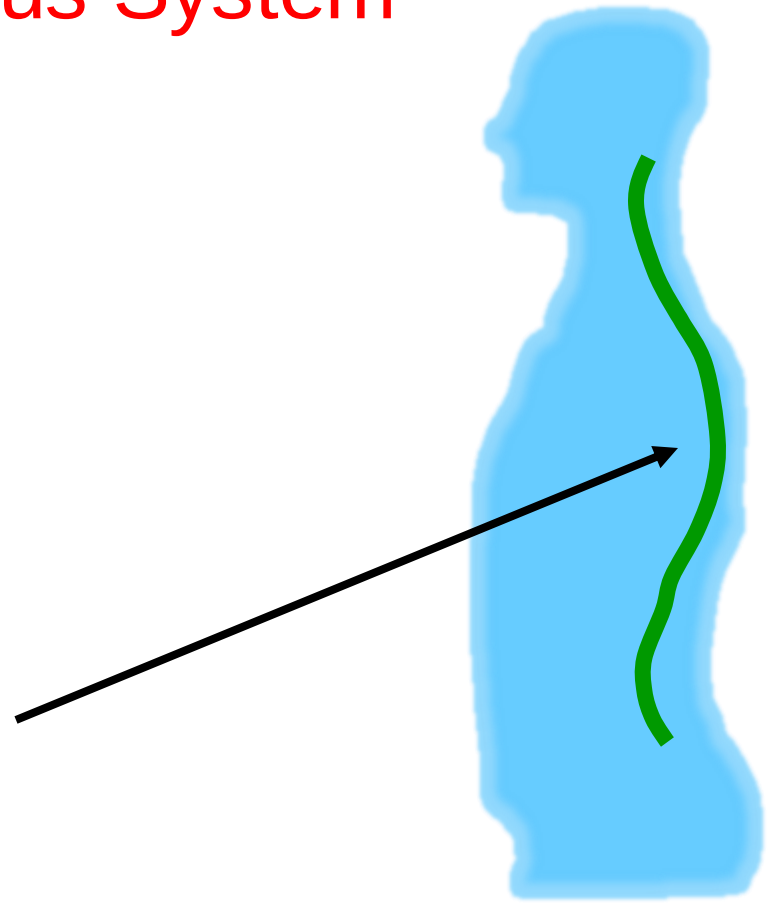
Operational Architecture of Biological Intelligence*



*An amazingly sweeping generalization for the purpose of metaphor

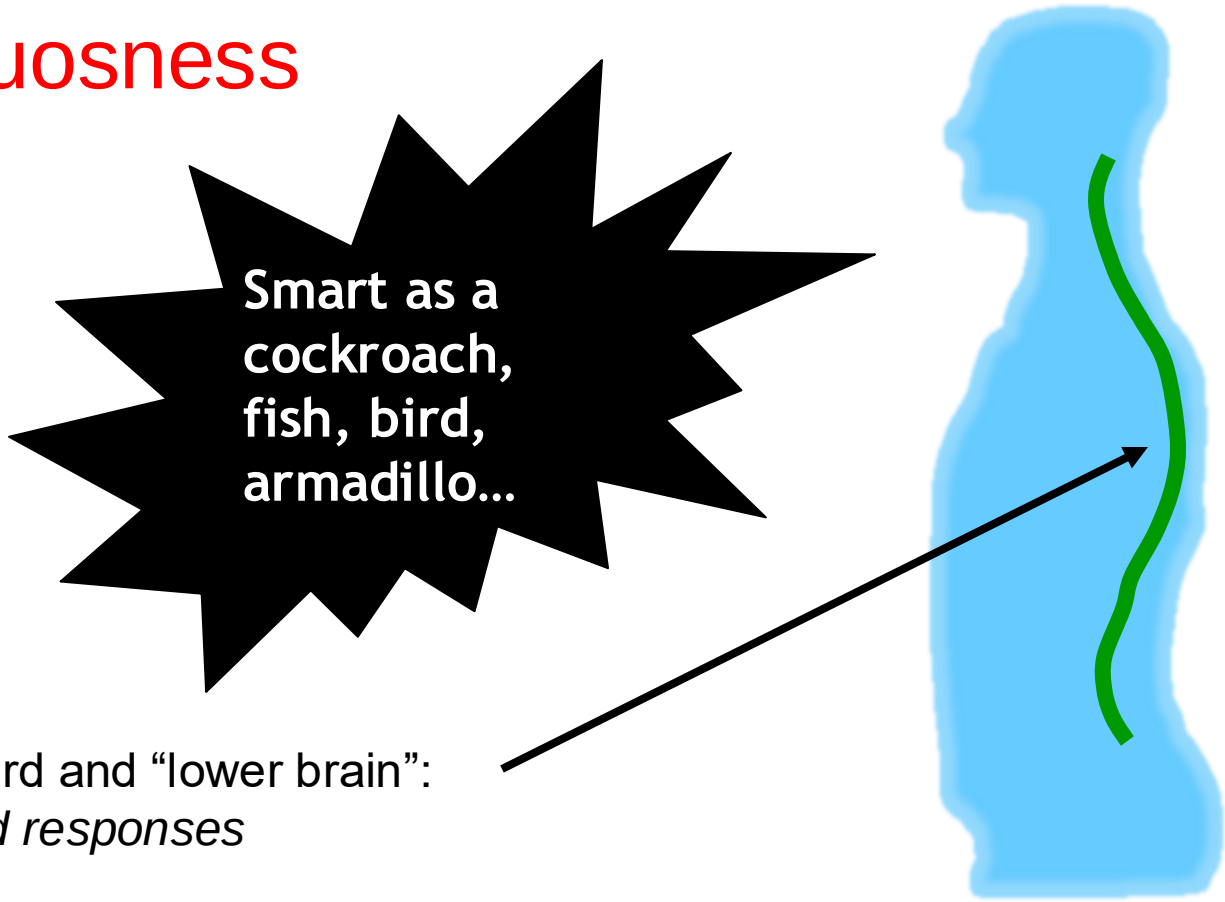
Adapted from R.Murphy

Lower Central Nervous System



Spinal cord and “lower brain”:
Skills and responses

Loop 1: Reflexes, reactive, unconsciuosness

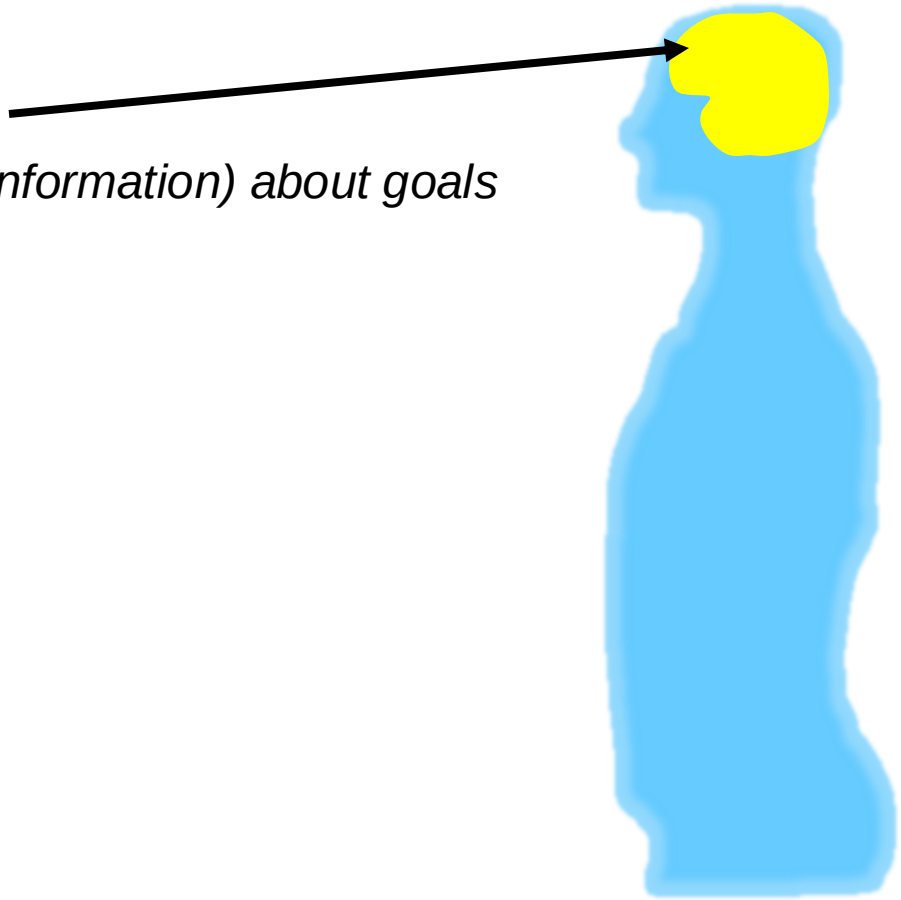


Spinal cord and “lower brain”:
Skills and responses

Brain

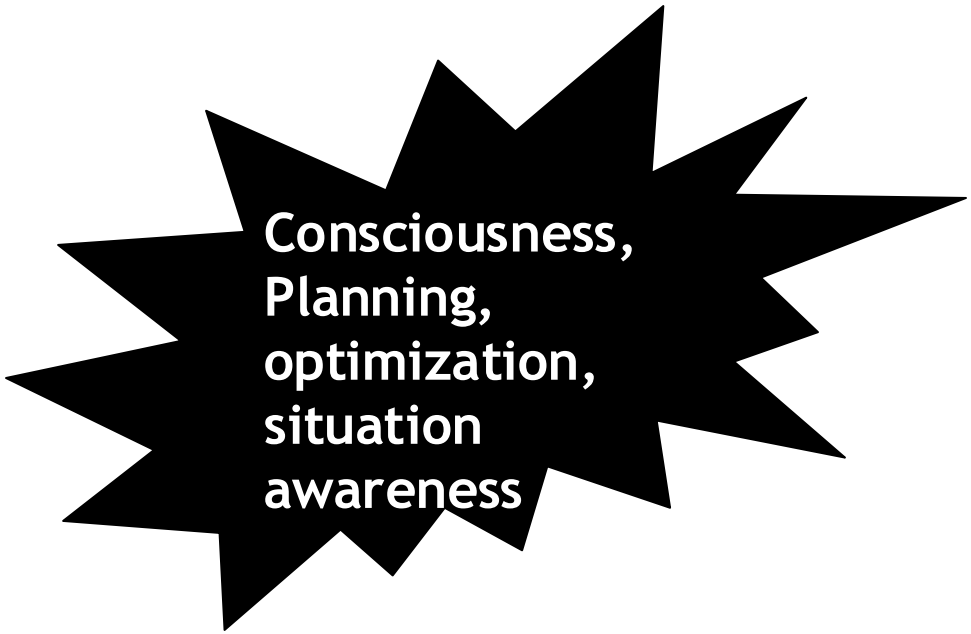
"Upper brain" or cortex

Reasoning over symbols (information) about goals



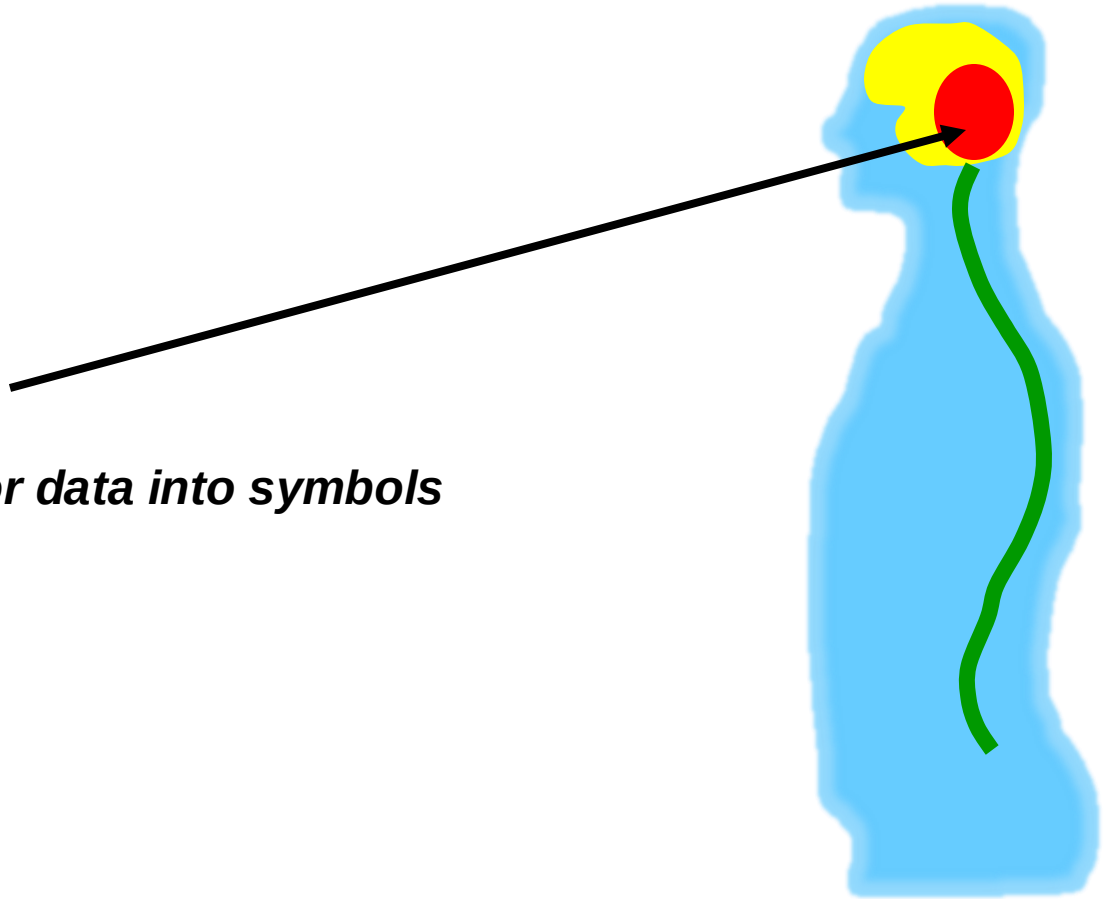
Loop 2: Deliberative, thoughtful, conscious

"Upper brain" or cortex
Reasoning over symbols (information) about goals



Adapted from R.Murphy

Midbrain (or mesencephalon)



"Middle brain"
Converting sensor data into symbols (information)

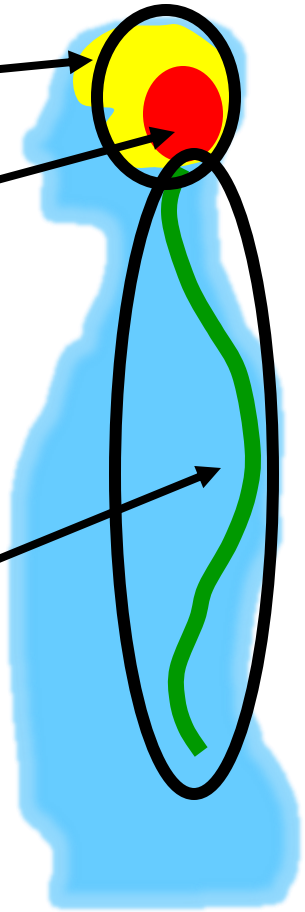
Adapted from R.Murphy

Two Loops Plus a Transform

"Upper brain" or cortex
Reasoning over symbols (information) about goals

"Middle brain"
Converting sensor data into symbols (information)

Spinal cord and "lower brain":
Skills and responses



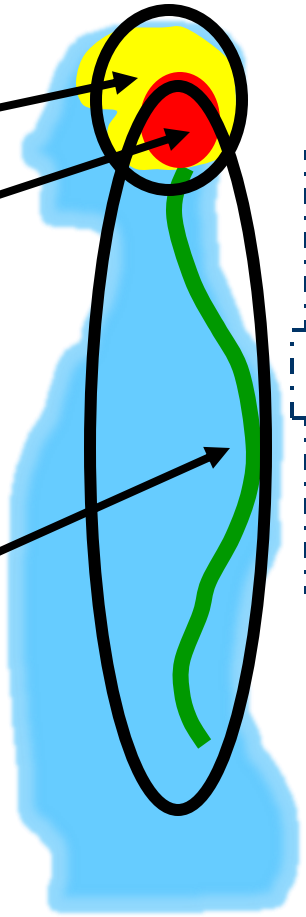
Adapted from R.Murphy

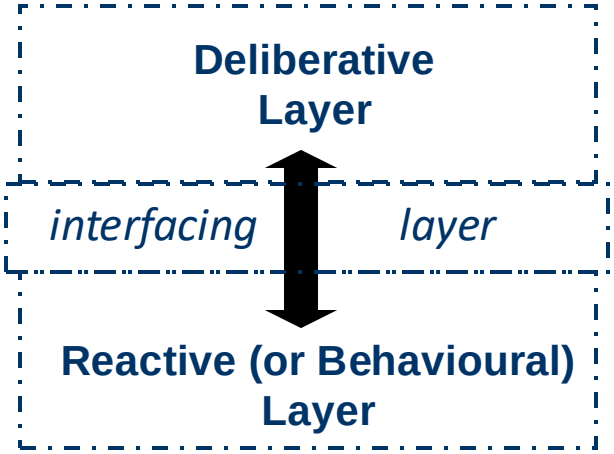
Two Layers in Architecture

"Upper brain" or cortex
Reasoning over symbols (information) about goals

"Middle brain"
Converting sensor data into symbols (information)

Spinal cord and "lower brain":
Skills and responses





Adapted from R.Murphy

But in Animals there is also "Emotional Intelligence"

User Interfaces

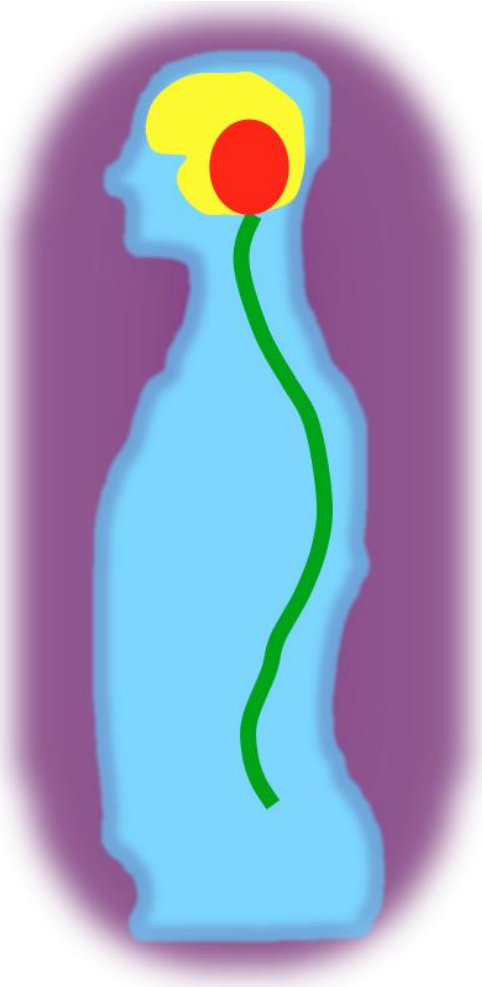
- Displays, transparency of what robot is doing/thinking
- Natural Language, gestures

Working in teams

- Explicit multi-agent coordination often relies on "social rules" (though implicit swarm intelligence may not)

"Persona" we present to others

- Security: what can you at your security grade can see about me
- Human-robot interaction: affective responses, natural language



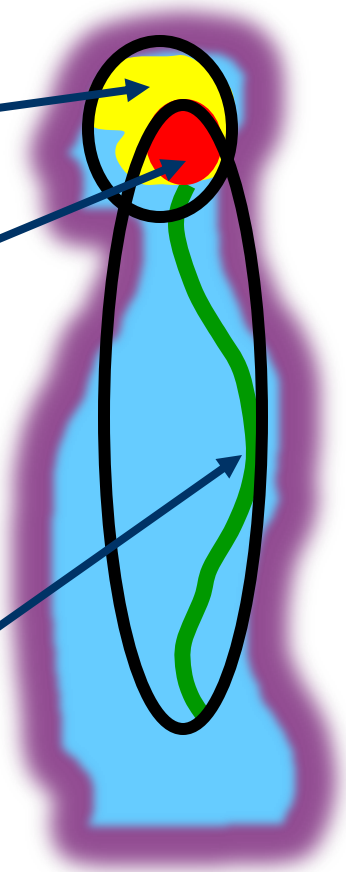
Adapted from R.Murphy

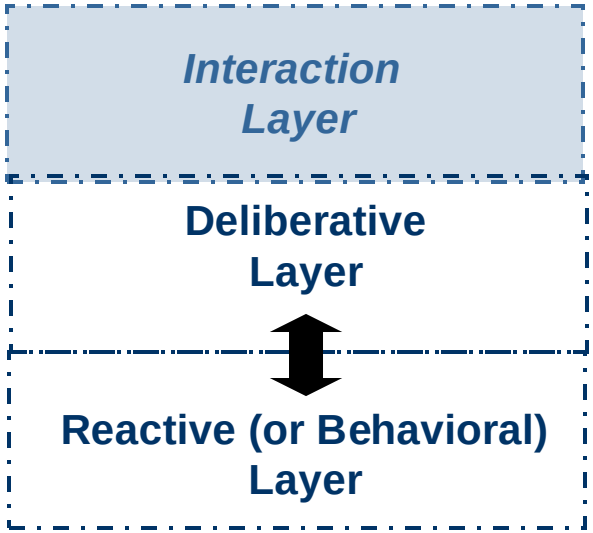
The Extended Canonical Architecture

"Upper brain" or cortex
Reasoning over symbols (information) about goals

"Middle brain"
Converting sensor data into symbols (information)

Spinal cord and "lower brain":
Skills and responses





Adapted from R.Murphy

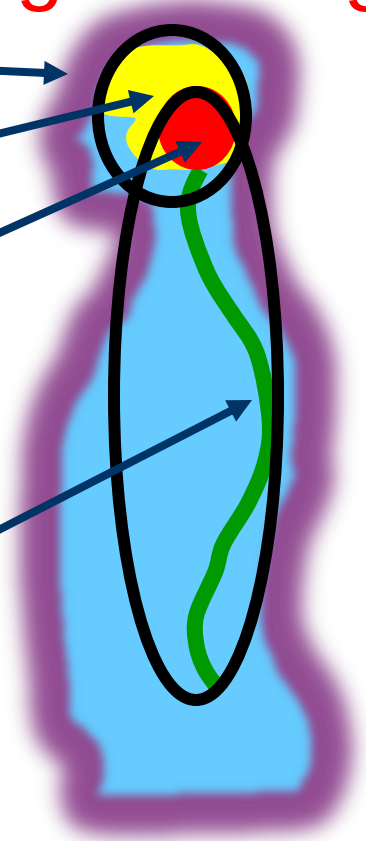
The Operational Architecture of biologic intelligence

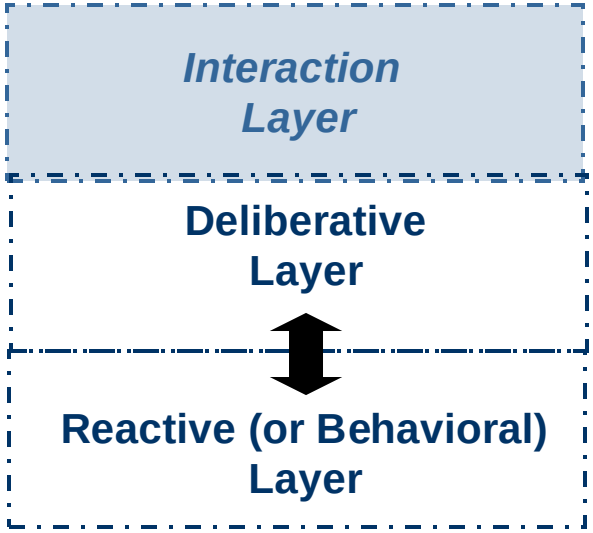
Interaction:
Persona and teaming

Deliberative loop:
Reasoning over symbols

Converting sensor data into symbols
(Key Functionality)

Reactive loop:
Skills and responses





Adapted from R.Murphy

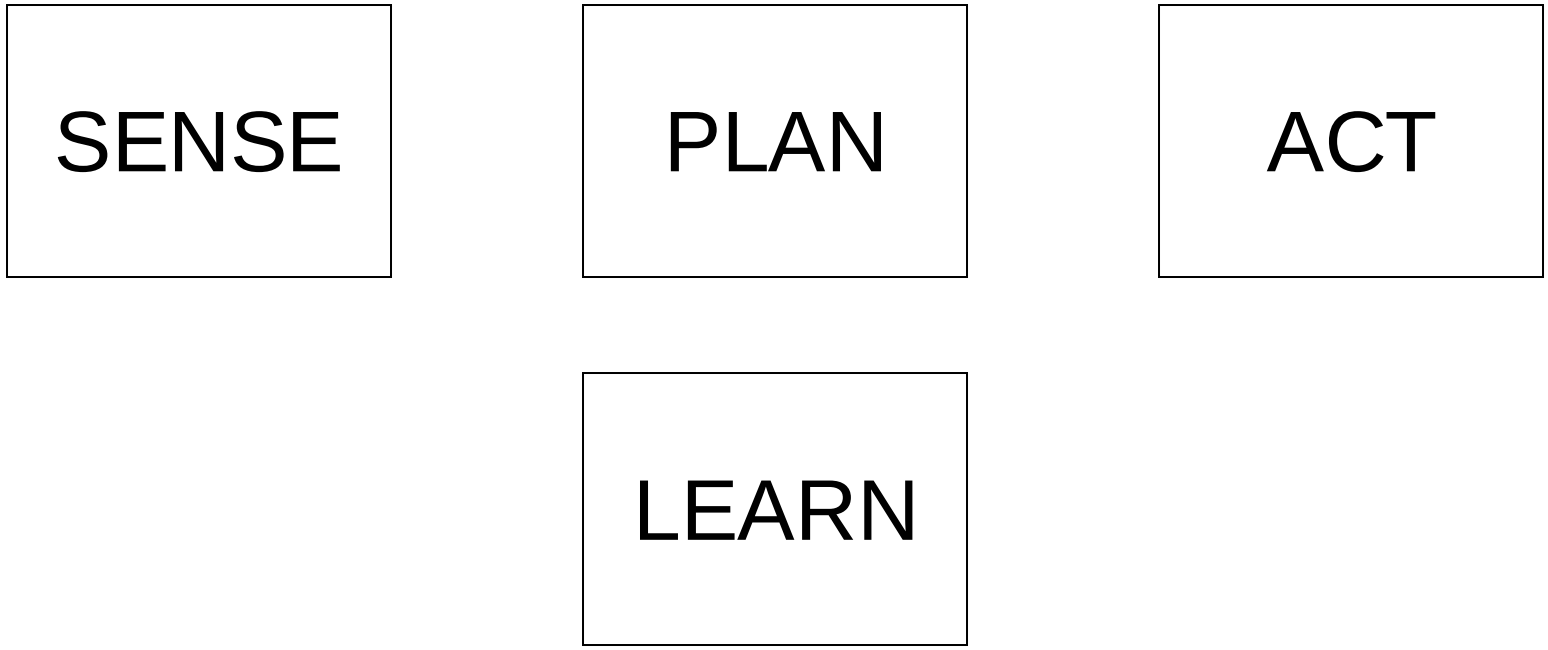
The Hard Part

- From Reactive to Deliberative
  - Two types of perception: DIRECT, **RECOGNITION (symbols)**
    - Impacts computer vision
  - Different time horizons
    - From Present to Present, Past, Future
    - Impacts sensing, storage, as well as algorithms reasoning, projecting
  - **Need a central structure (WORLD MODEL) to hold the symbols, history, knowledge but is tractable**

- From Reactive/Deliberative to Interaction
  - **Additional knowledge "theory of mind"– beliefs, desires, intentions (BDI) of the other agent, common ground**

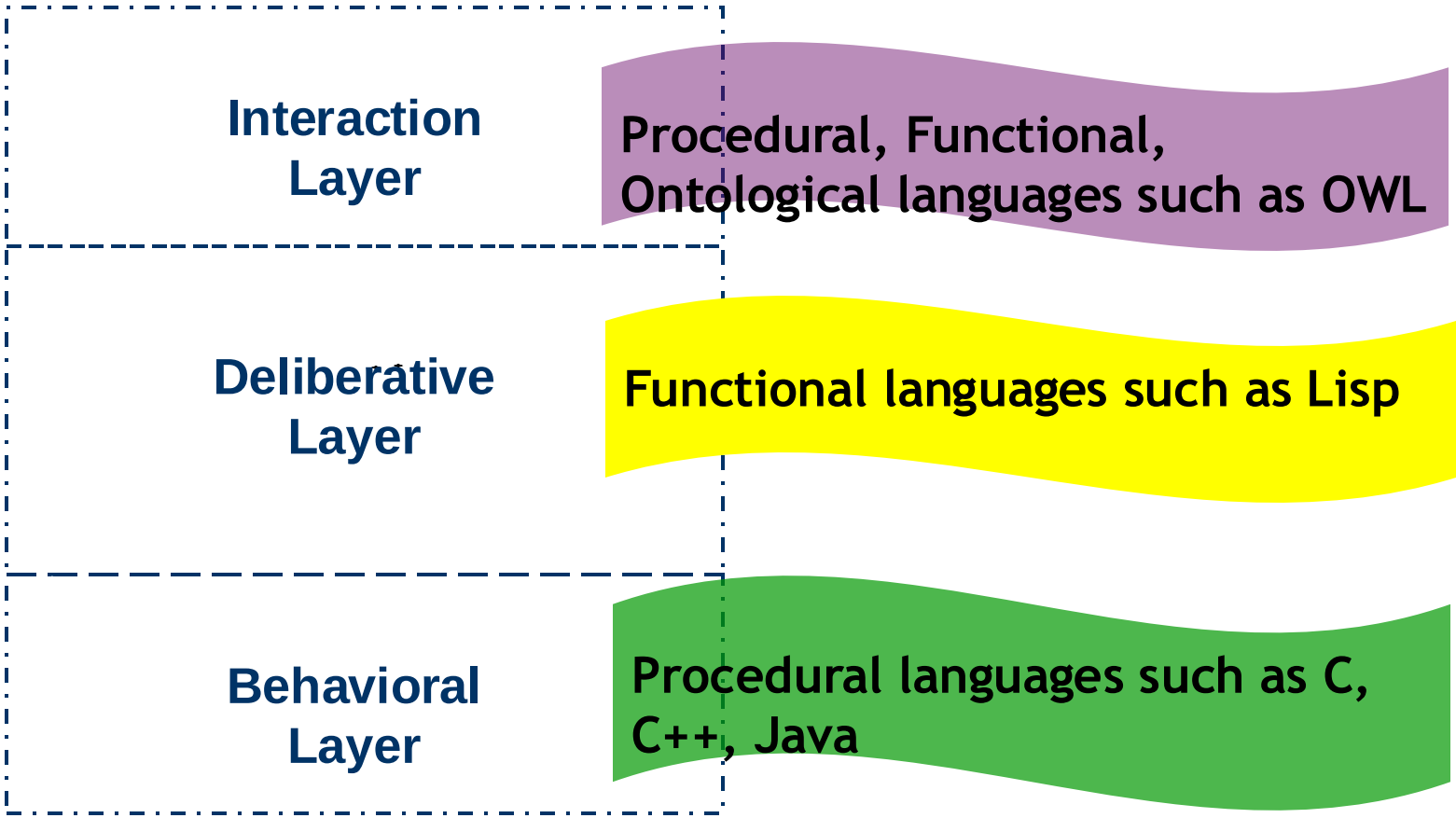
Can we make this more tangible?

Classical Primitives for Robot Intelligence



Problem: not everything intelligent requires “deciding” (ex., reflexes or muscle memory such as riding a bike or driving a car)

Programming Languages



Adapted from R.Murphy

So Far

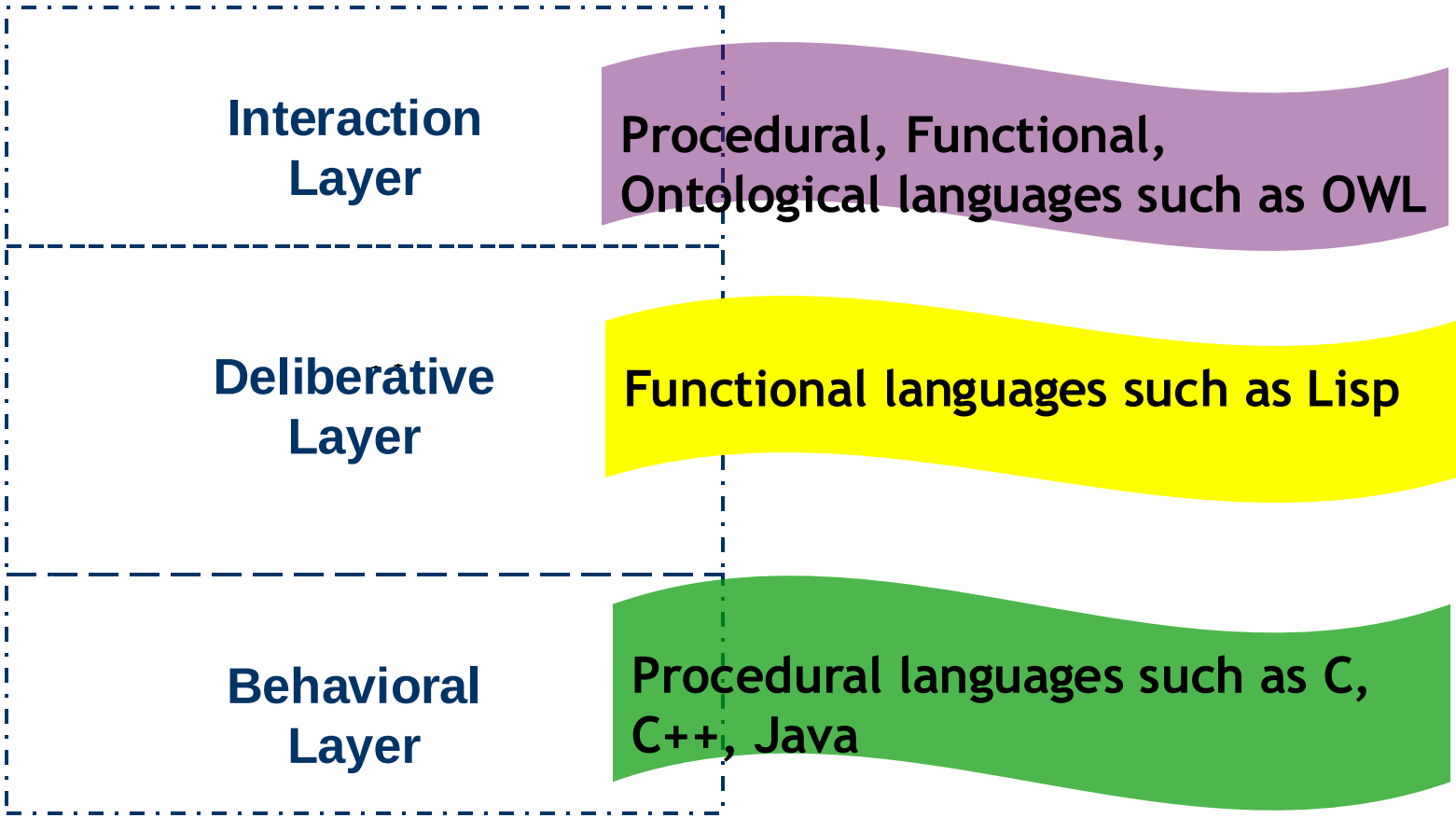
- Biological organization suggests three layers of intelligence with distinctly different perception, knowledge, planning horizons, and time scales

- The AI Robotics field has converged on ***"PLAN, then SENSE-ACT*** *with LEARN*" as needed at different points
  - Technically this is SENSE-PLAN, SENSE-ACT but historically the sensing for planning just like the execution monitoring is lumped in "PLAN"

- *But still not as tangible as desired…*

Adapted from R.Murphy

Programming Languages



Adapted from R.Murphy

Advantages of programming in layers with different styles

- Decomposition of a complex system
  - Can use a separate processor(s) for each layer or behaviors
  - Can split between on-board, off-board
- Matching right tools and mindset for the task
  - Ex. C++ for behaviors, Lisp for planning
- Add to working, verified code

Adapted from R.Murphy

Can intelligence be added in layers? Like upgrading to "pro version" or downloading "apps" as needed?

Adapted from R.Murphy

Can intelligence be added in layers? Like upgrading to "pro version" or downloading "apps" as needed

- Yes, intelligence is organized in layers
- Yes, Can create libraries of equivalent ("logical") algorithms
- But as will be seen in later lectures…
  - Adding new behaviors or algorithms is non-trivial
    - Coordination functions at reactive layer impose certain assumptions, restrictions, and side effects
  - Adding another layer is non-trivial
    - Different attributes such as perception, models require significant design investment
    - "Hidden" coordination between layers

Adapted from R.Murphy

How Much Artificial Intelligence Does A Robot Need?

Adapted from R.Murphy

How Much Artificial Intelligence Does A Robot Need?

- It depends…
- What functions does the robot need to do?
  - Generate? Monitor? Select? Implement? Execute behaviors? Learn?
- What planning horizon does the functions require?
  - Present, Present+Past, Present+Past+Future
- How fast do the algorithms have to update?
  - May have to use a closed world and guaranteed execution rates (control theory)
- What type of model does the robot need? Local? Global? Both?
  - Note: go with the minimum

Adapted from R.Murphy

SUMMARY AND ADDITIONAL THOUGHTS

ARCHITECTURE: Summary

- **An architecture is the Big Picture of how to program an intelligent robot**

- **"Architecture" refers to either**
  - The *operational architecture* which described what the system does on an abstract level
  - The *system architecture* developed by a manufacturer (or research group) and may look like a data flow diagram
  - The *technical architecture*, specifies the actual techniques and code organization

- **The canonical operational architecture for an AI robot consists of three layers which generally represent different programming styles or even implementation languages:**
  - Behavioral
  - Deliberative
  - Interaction

Adapted from R.Murphy

ARCHITECTURE: Other Observations

- Current practice is good with deliberative functions operating on symbols, good with behaviors using direct perception
- Major barrier is going from sensory data to symbols: recognition and labeling as unique instances
  - May be able to see a coffee cup but not that it is my coffee cup and yours from the same dish collection is over there
- Major barrier in understanding human intention (which is often implied but never spoken); AI robots currently require explicit directions

Adapted from R.Murphy

Future Questions and Lectures

- Since some aspects seem beyond current programming capabilities, what are levels of autonomy in terms of how much the robot can be trusted to do and how much the human has to do?
- What is the systems architecture for the hybrid architecture?
- Where do the 7 areas of AI fit in with the operational architecture?

Adapted from R.Murphy