Methods in AI Research 8
Cognitive Modeling:
What is it & why should you care?

Chris Janssen

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www.cpjanssen.nl

- **About me**
- **Administrative things**
- **The interesting content - lecture ☺**

My various hats

- Assistant Professor, Experimental Psychology
- Programmaraad ('board member') of MSc AI
- Area coordinator of Cognitive Modeling & Processing
- Lecturer on various courses

My background

- AI, HCI, & Cognitive Science
- Groningen – RPI – UCL – Xerox Parc – Microsoft Research – Smith-Kettlewell – Utrecht
- Domain: Multitasking & Distraction
  Humans in Autonomous driving
  Applied Research
- Methods: Modeling & Experimentation

See: van der Heiden RMA, Janssen CP, Donker SF, Hardeman LES, Mans K, & Kenemans, JL (2018) Susceptibility to audio signals during autonomous driving. PLOS ONE 13(8): e0201963. https://doi.org/10.1371/journal.pone.0201963
(not exam material ☺)

More about my research

- www.cpjanssen.nl

- **Youtube channel** (some research summary clips): https://www.youtube.com/channel/UCkqHNyN02_T-reH8PzILL0w/

- About me
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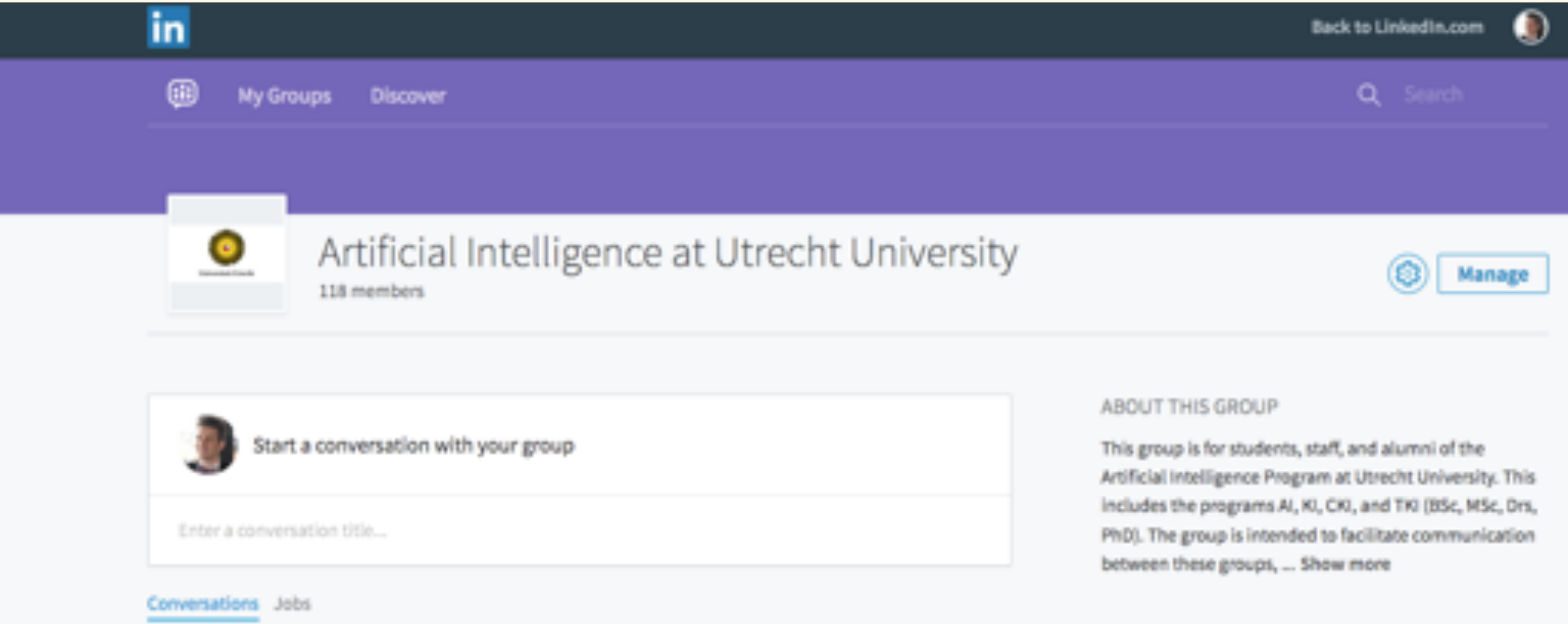
Plug: LinkedIN AI @ Utrecht group



(state clearly in your profile that you are an AI student in Utrecht)

My classes: methods covered

- 1/10: Cognitive modeling
- 3/10 Experimentation
- 8/10 Scientific writing
- 10/10 Designing & Evaluating AI and Automated systems

My classes: preparation & deadlines (see blackboard)

- 1/10: Anderson, J. R. (2002). Spanning seven orders of magnitude: a challenge for cognitive modeling. *Cognitive Science*, *26*(1), 85–112.
- 3/10: Cairns, P. (2016) Experimental Methods in Human-Computer Interaction. In Soedergaard, Dam (Eds.) *The encyclopedia of Human-Computer Interaction* (2nd edition). Online available at: https://www.interaction-design.org/literature/
- 8/10:
  - Before 7/10 at noon, hand in "Fantasy abstract" via Blackboard individually
  - Before lab: read lab assignment (of part 2)
- 10/10:
  - Extra office hour to ask questions about assignment in building "Langeveld", Heidelberglaan 1, room H0.12 (follow signs to "floor 0", then to "section H")
- Week of 12/10: Chris in China (no e-mail)

Exam - Of this lecture know:

- **All the material that was discussed in class**
- **Article**
  - **Anderson, J. R. (2002). Spanning seven orders of magnitude: a challenge for cognitive modeling. *Cognitive Science*, *26*(1), 85–112.**
- **Slide appendix:**
  - **Study questions to give rough guideline of most important aspects to note when reading the article. For exam: know these, so you can *apply* knowledge to case studies**
  - **Example exam questions from previous year(s) also at end of slides**
  - **Additional material to help in studies**
- ***These topics are new to many of you:***
  Start reading and studying *early* (during my next lecture you can ask me questions about the paper)

- About me
- Administrative things
- **The interesting content ☺**

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Cognitive Modeling:
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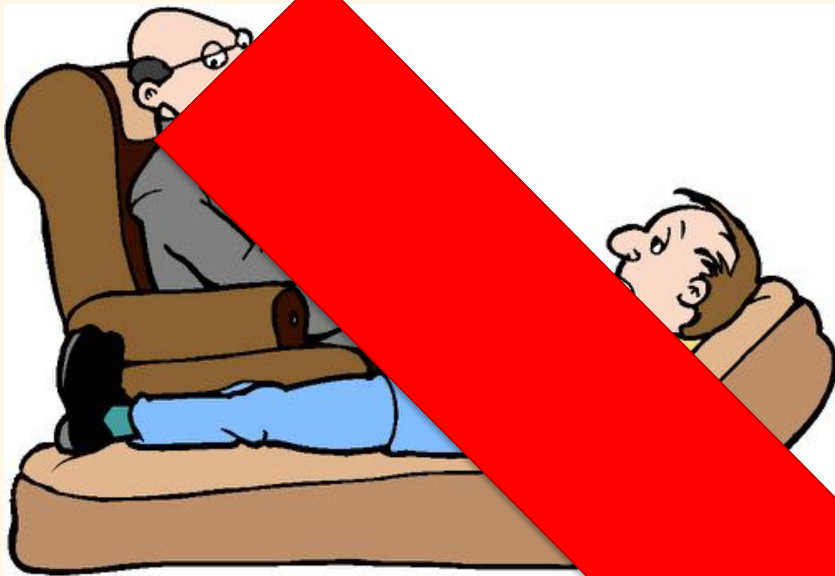


In spirit of Dartmouth workshop

"The study is to proceed on the basis of
the conjecture that every aspect of
learning or any other feature of intelligence
can in principle be so precisely described that
a ***machine can*** be made to ***simulate*** it."

Some topics:

- ✓ Language processing & -production
- ✓ Neural nets (cognitive modeling)
- ✓ Abstraction (from sensor data to concepts)
- ✓ Creativity

Today's topics

- Why use models?
  - In science
  - In practice / industry
- What is a cognitive architecture?
  - What are the (dis-)advantages?
  - What is contrast with cognitive model?
  - Example: multitasking in ACT-R
- What makes a good model?
  - Level of abstraction
- If you want to know more…
- *Appendix: more info that is useful for exam!*

Psychology: Diverse field

Memory

Emotions

Language

Visual perception

Learning

Math

Physics: Converging field

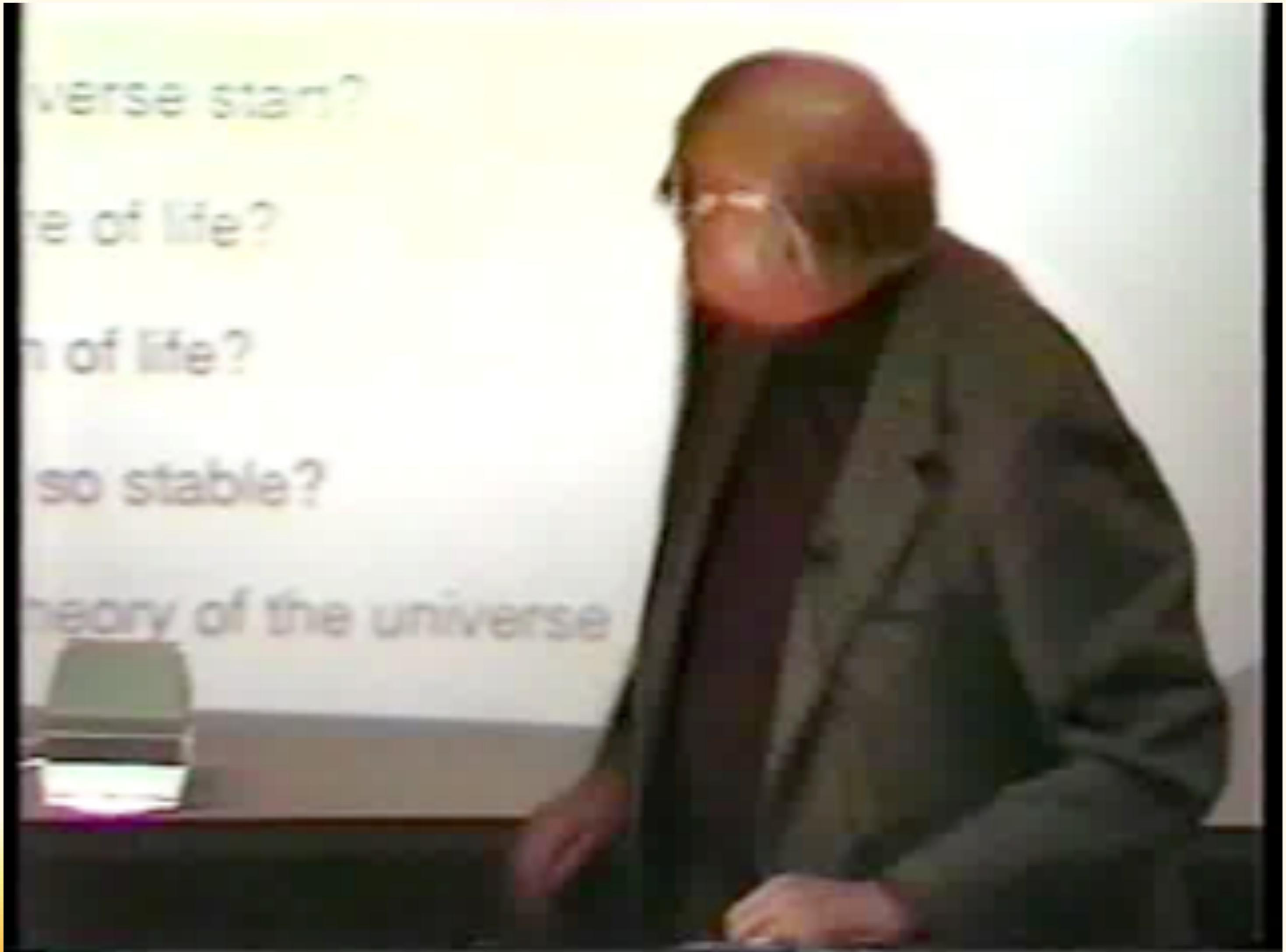
Core idea of Cognitive Modeling (& AI)

- **'Make psychology more like physics'**

- **How can the mind occur in the physical universe?**

➔Unified Theory of Cognition (Allen Newell, 1990)

http://act-r.psy.cmu.edu/misc/newellclip.mpg



Why use computer models/simulations?

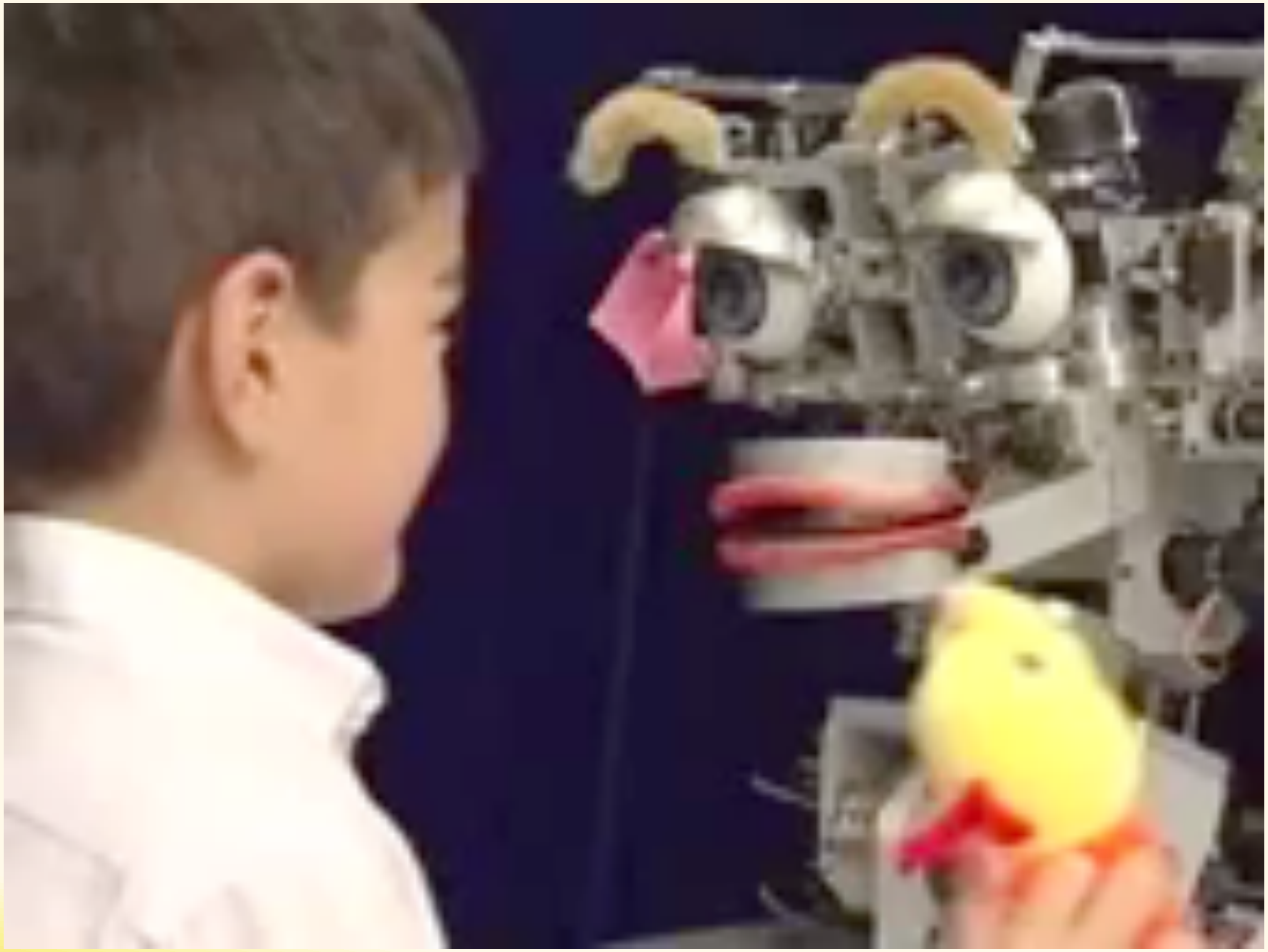
1. ***Formal*** **specification of a theory: working code**
2. **Working code is *detailed***
   – **Allows for scrutiny & scientific discussion**
3. **Model can make *predictions***
4. **Understanding by *building***

- **Like physics:**
  – **Describe nature using equations**
  – **Apply equations to dataset / situation**

Understanding by building

Robocup Standard League Finals 2014

Understanding by building



MIT's Kismet

Understanding by building

See: http://cog.cs.drexel.edu/distract-r/

Why use computer models/simulations?

1. ***Formal*** **specification of a theory: working code**
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4. **Underst... ...uilding**

Scientific motivation

- **...physics:**
  – Describe nature using equations
  – Apply equations to dataset / situation

Why use models in practice/industry?

- **Examples:**
  - Intelligent tutor systems
  - Intelligent game opponents
  - Usability test
  - Adaptive interface: interruptions

➔ ***Applied systems informed by theory***

Intelligent tutor systems

- $2X + 7 = 27$

  $X = ?$
- Answer student: $x = 17$

- Questions a tutor system addresses:
  - What went wrong? (and how did this happen?)
  - What to practice next?
  - What instructions should be given?

Intelligent tutor systems: State of the art

- **www.rekentuin.nl >1800 schools**

Intelligent tutor systems: State of the art

Anderson, J. R., Betts, S., Ferris, J. L., & Fincham, J. M. (2012). Tracking children's mental states while solving algebra equations. *Human brain mapping*, *33*(11), 2650-2665.

For video see: http://act-r.psy.cmu.edu/wordpress/wp-content/uploads/2013/09/kidalg_mix_ascaled_text1.mp4

Intelligent game opponents

"Beating the human" – not our goal

Intelligent game opponents: State of the art

https://www.youtube.com/watch?v=ApIG6KnOr2Q

Intelligent game opponents: State of the art

https://www.youtube.com/watch?v=FAU2l4ZgDsw

Siebert, Gray, Lindstedt (2017) Topics in Cognitive Science

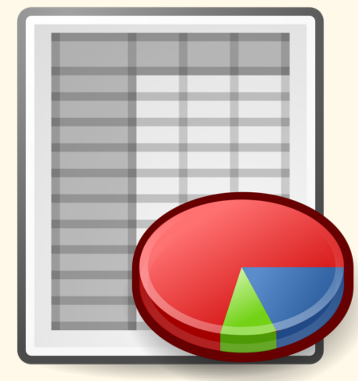
Intelligent game opponents: State of the art

Sangster, Gray (2017) MathPsych; Sangster, Medonca, Gray (2016) Human Factors conference

Usability Test: Distract-R

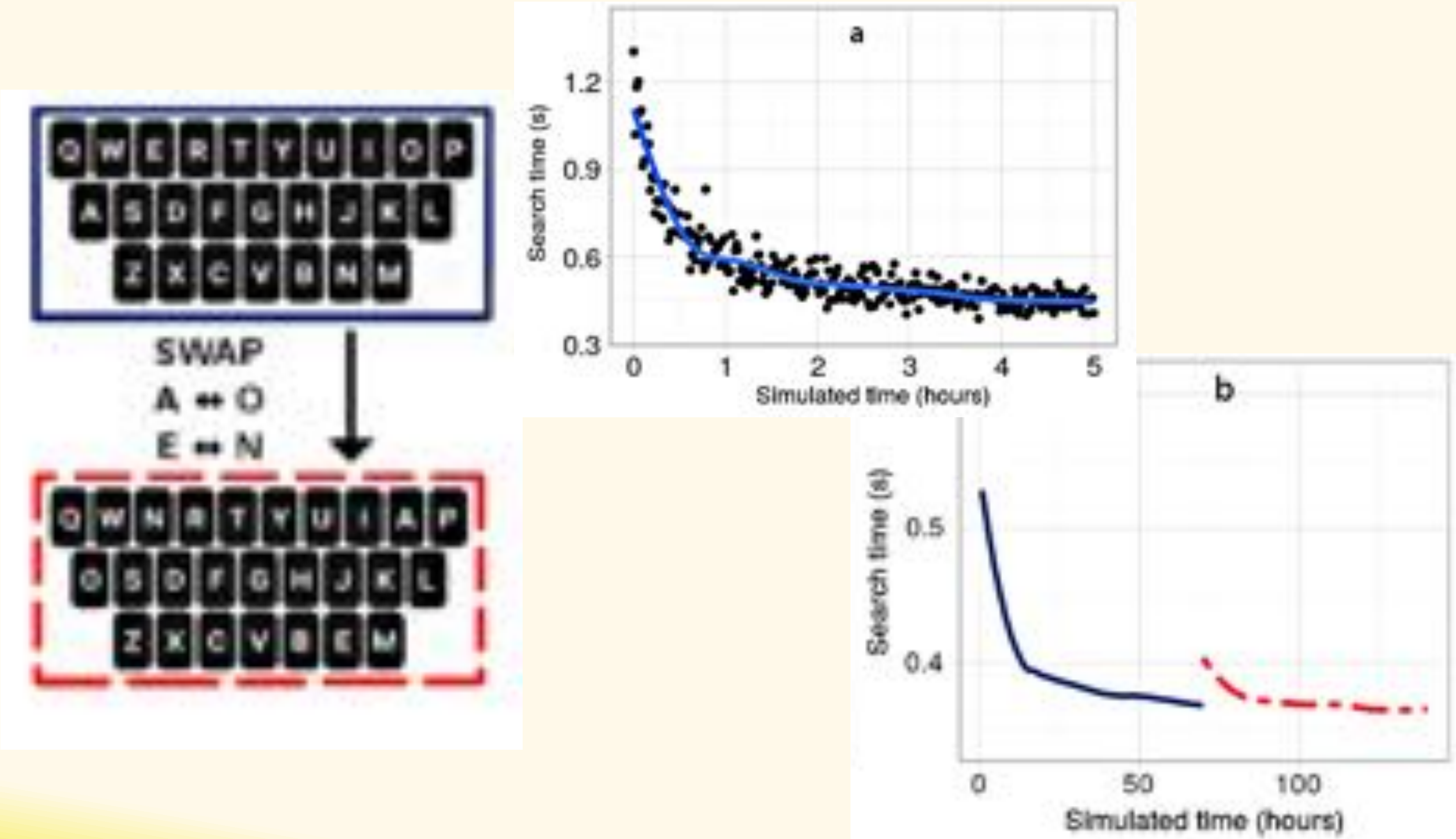
See: http://cog.cs.drexel.edu/distract-r/
Brumby, D. P., Janssen, C. P., Kujala, T., & Salvucci D.D. (2018). Computational Models of User Multitasking. In Oulasvirta et al (Eds.) *Computational Interaction*, 341-362.

Adaptive interface: interruptions



Iqbal, S. T., & Bailey, B. P. (2010). Oasis: A framework for linking notification delivery to the perceptual structure of goal-directed tasks. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *17*(4), 15:1–28.

Software & interface (re-) design



https://users.aalto.fi/~jokinej10/visual-search/

Jokinen et al (2017; CHI)

Why user models for practice?

1. Have human-like experiences
   - Game opponent -> requires understanding first
2. Make appropriate, (adaptive) decisions due to understanding of user:
   - Feedback (tutor)
   - Difficulty (game)
   - Usability
   - Adaptive interface (interruptions)
   - Software & interface (re-) design

Within context of your MAIR lab assignment

- **Intelligent conversational agent**
  - like a tutoring system

- **Keep track of user's**
  - Intentions, Needs, Attention, Memory, Actions, …
- **Use to make (pro-active) intelligent decisions:**
  - Remind of items that might be forgotten, anticipate actions, provide just-in-time feedback on actions
  - Given *model's* understanding *of user*
- **Implementation beyond scope for MAIR**

Today’s topics

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  - In science
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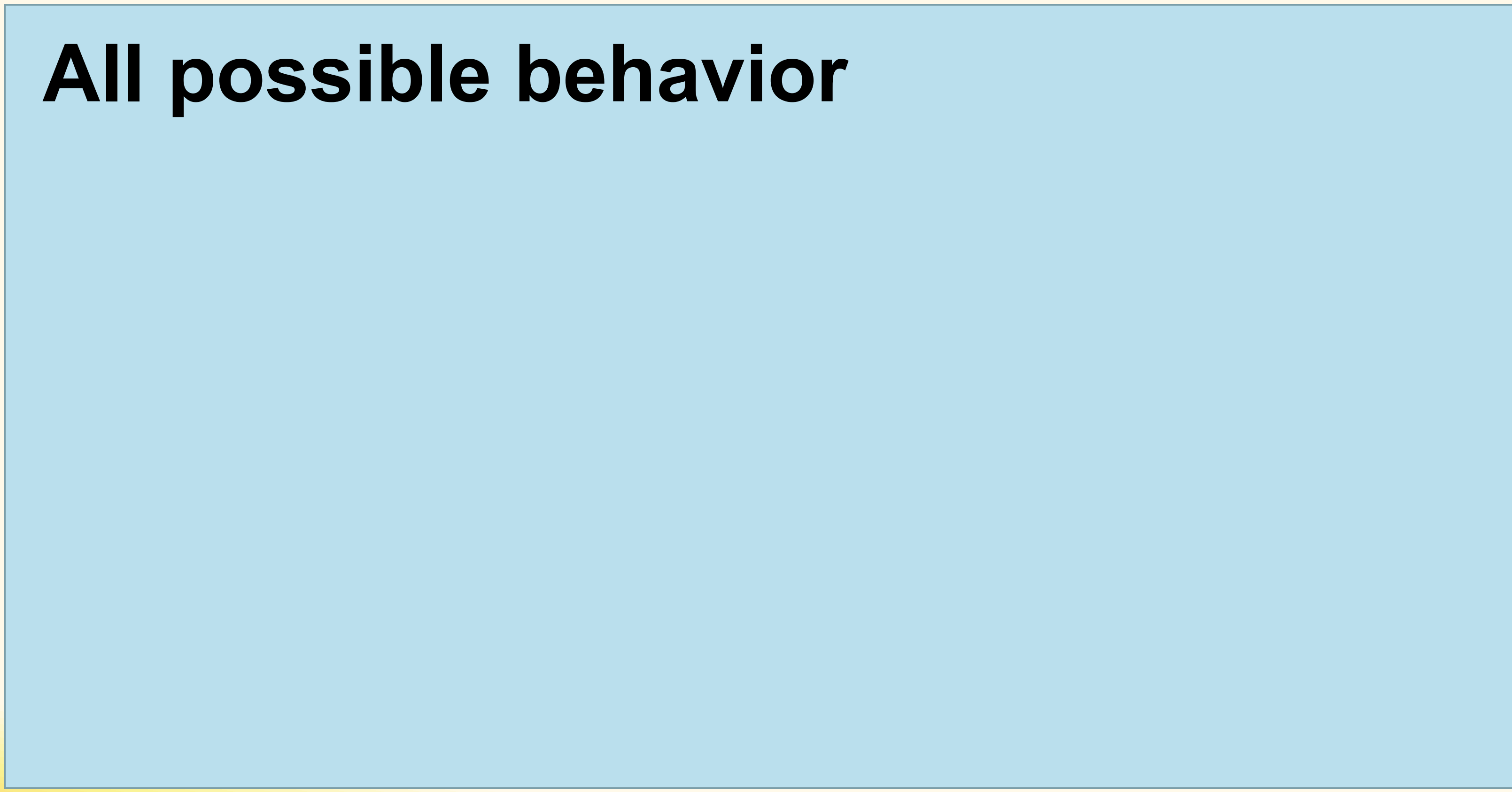
- What is a cognitive architecture?
  - What are the (dis-)advantages?
  - What is contrast with cognitive model?
  - Example: multitasking in ACT-R
- What makes a good model?
  - Level of abstraction
- If you want to know more…

More about the basic science…

➔Unified Theory of Cognition (Allen Newell, 1990)

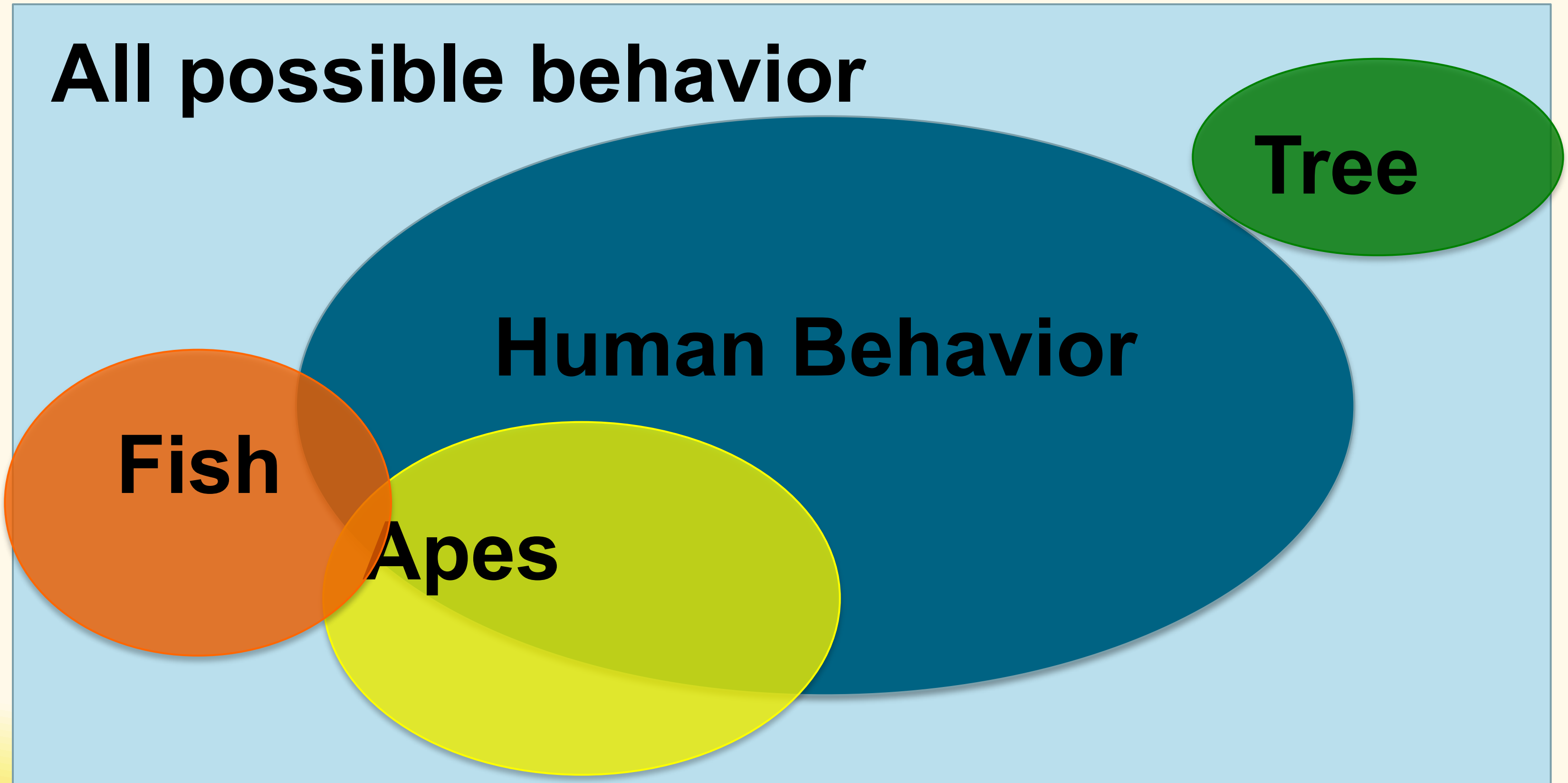
Unified Theory of Cognition

illustration with Venn Diagrams



Unified Theory of Cognition

illustration with Venn Diagrams



Unified Theory of Cognition

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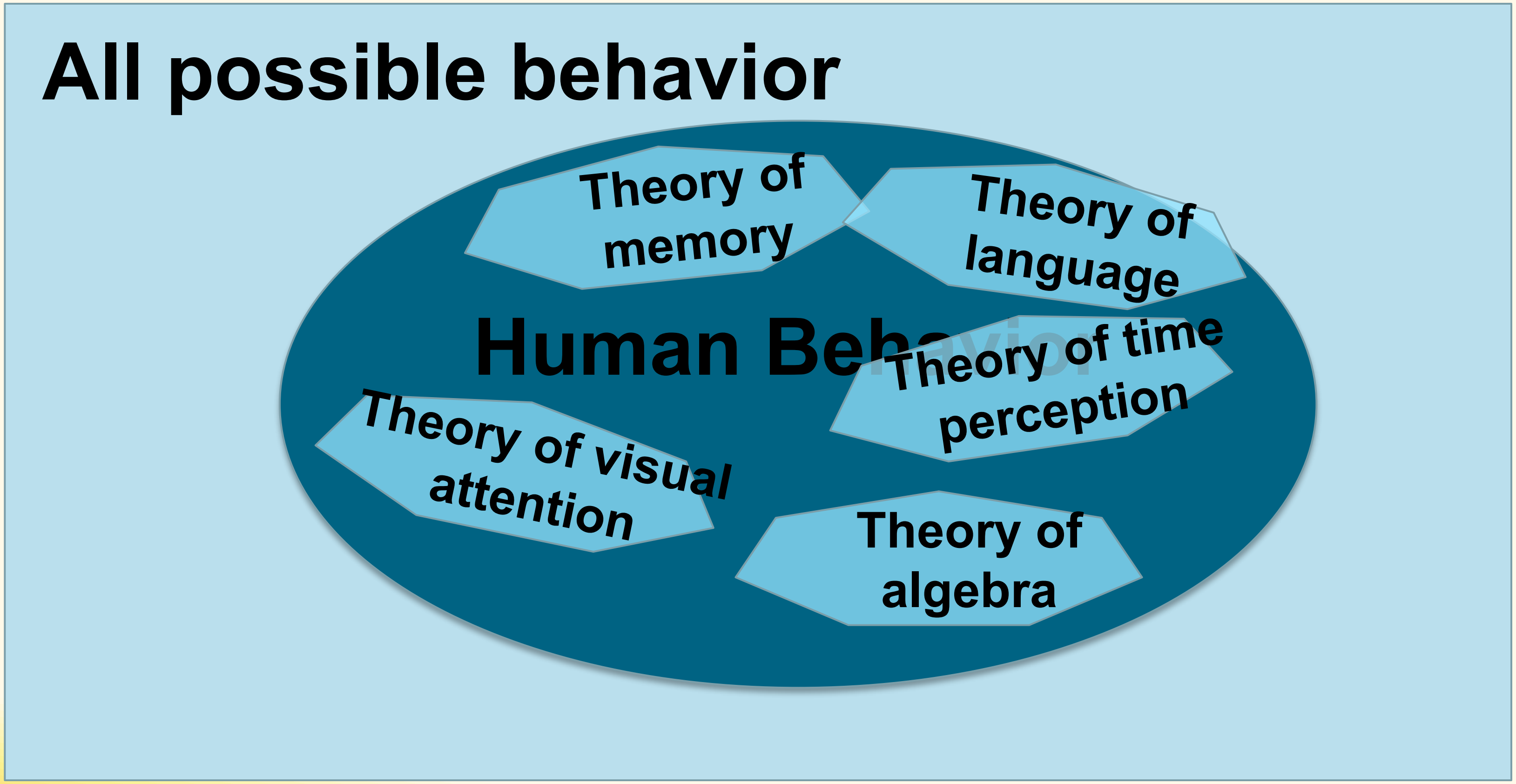
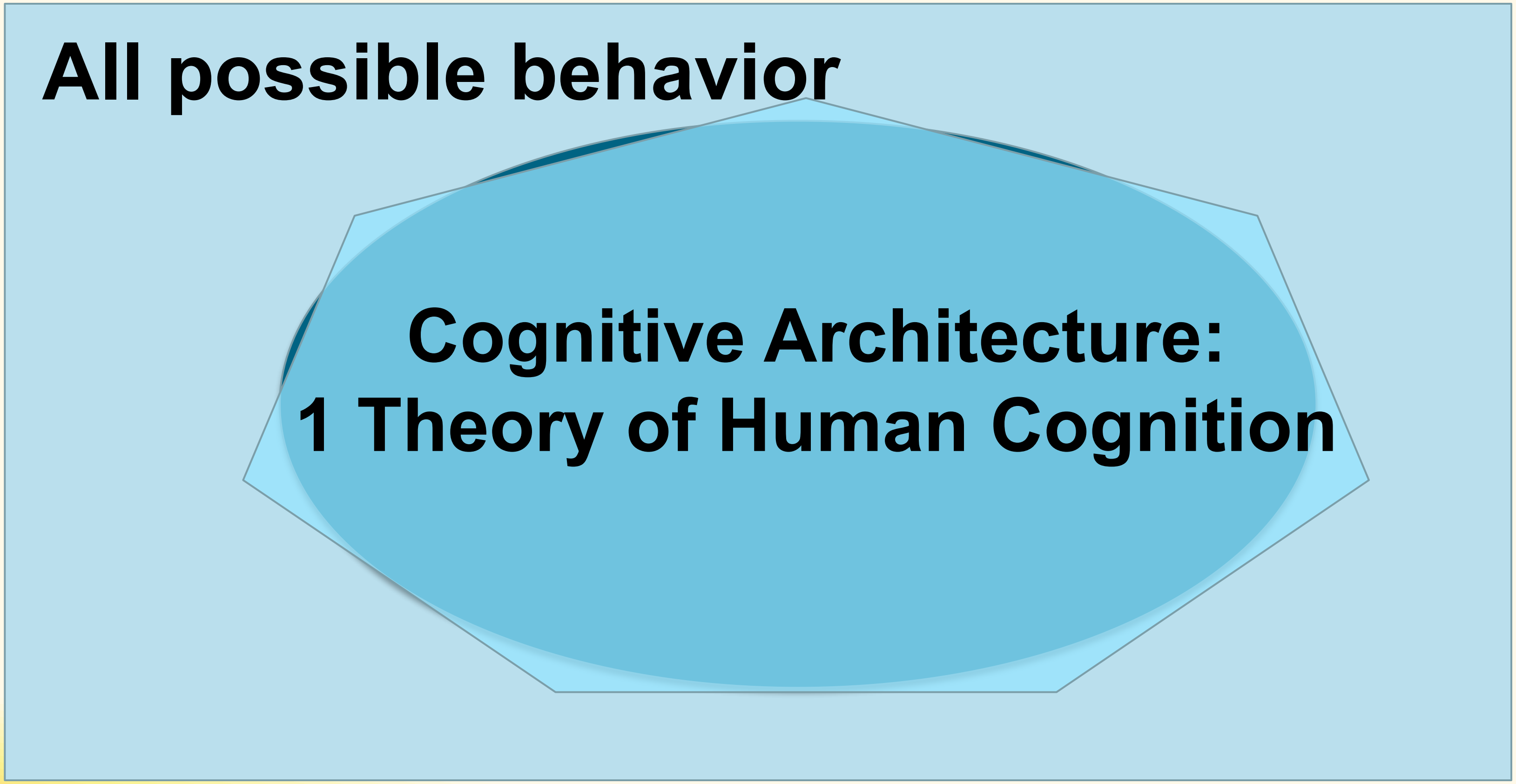


Unified Theory of Cognition

illustration with Venn Diagrams



Unified Theory of Cognition

- **Newell's goal:**
  - **Develop 1 theory that can describe (almost) all facets of human behavior**
  - **Describe interactions between theories of different domains/situations/components**

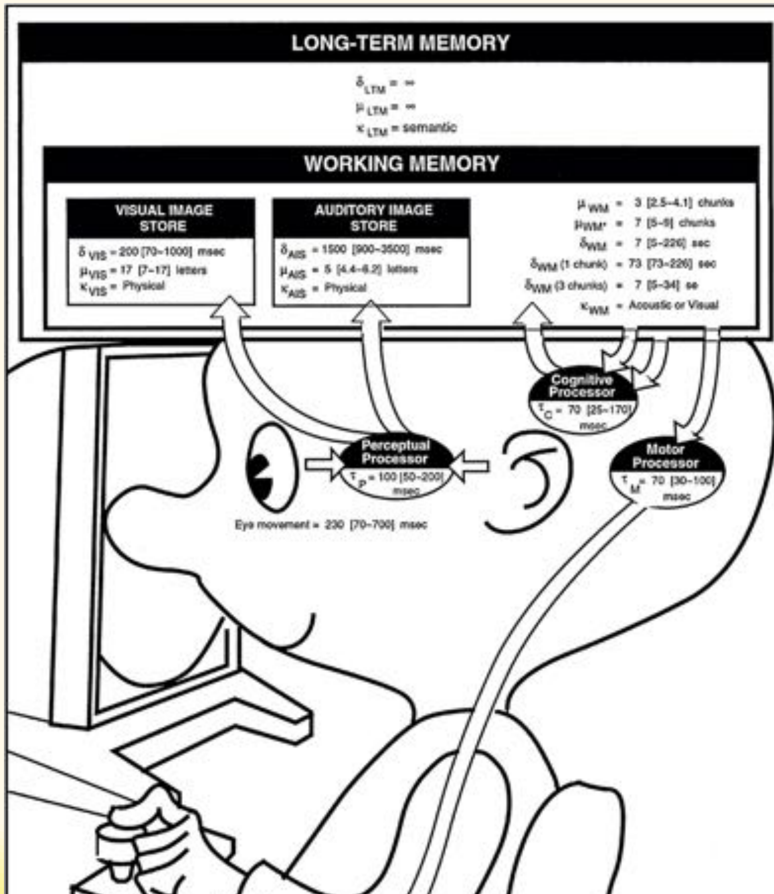
- ***Cognitive Architecture*** **(Bell & Newell, 1971)**
  - **Within the architecture you develop models of specific tasks/settings**

Example of Cognitive Model in Architecture

Cognitive Architecture & Cognitive Model

- **Cognitive *Architecture* (John Anderson, 2007)*:***
  "a specification of the <u>structure</u> of the <u>brain</u> at the level of abstraction that explains how it achieves the <u>function</u> of the mind"

- **Explains:**
  - What brain can & can't do (function)
  - How it does that (structure)
  - What *general* parameters and equations govern behavior



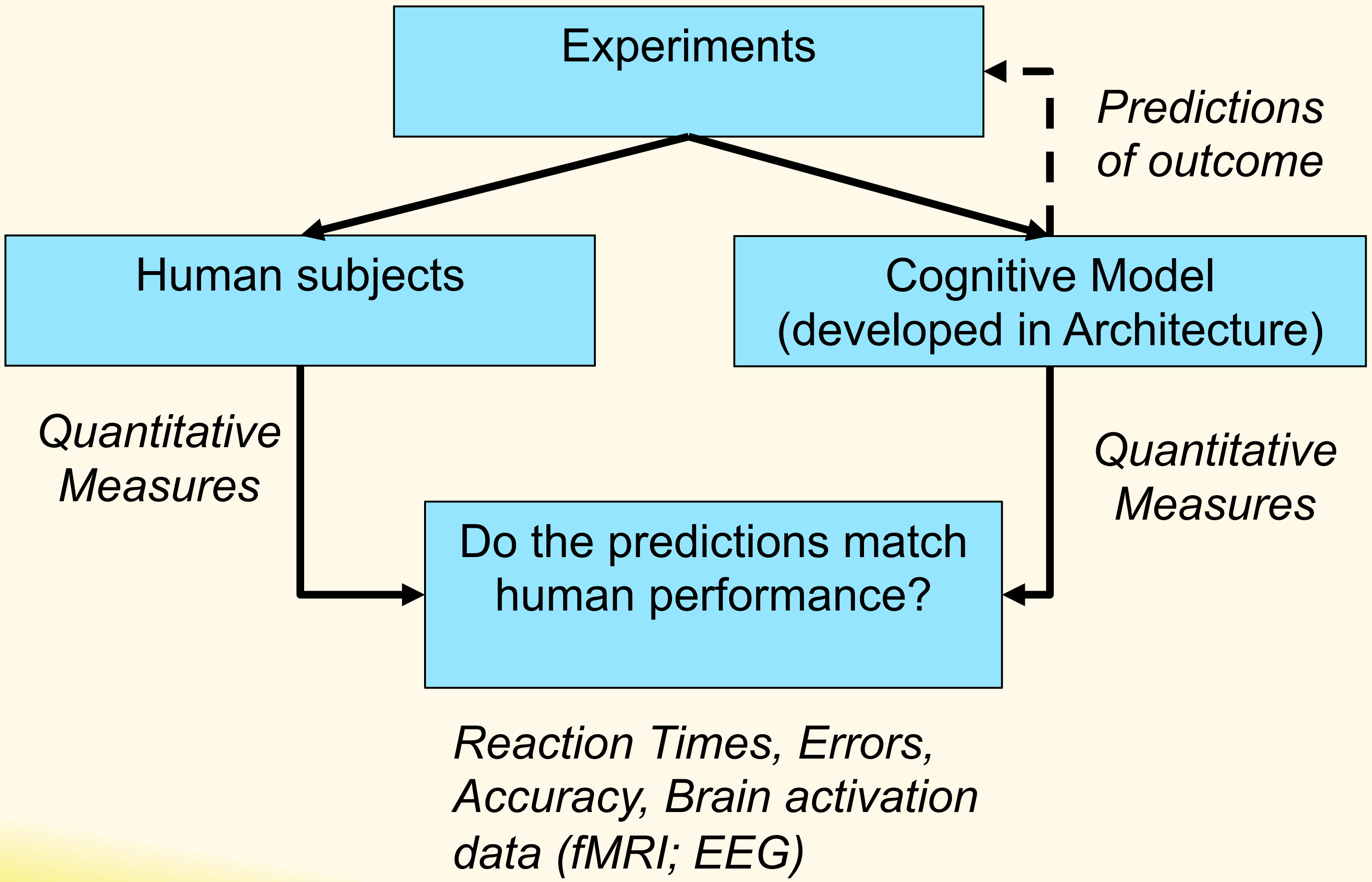
Cognitive Architecture & Cognitive Model

- Cognitive *Model*
  - A model of a *specific* task or process
  - Developed *within* or *inspired by* an architecture

Cognitive Architecture & Cognitive Model

- **Architecture questions:**
  - What is our general memory capacity?
  - How do we forget information over time in general?
  - How much visual information can we process per time unit?
  - How do we control our hands in general?
- **Model questions:**
  - How do we calculate 101 x 7 – 3 (given architecture)
  - How do we control a car (given architecture)
  - How do we divide time between driving and making a phone call (given architecture)

Testing a Model



Cognitive Architectures & Turing Machine

- Alan Turing (1936): Turing Machines can compute all 'computable' functions
  - Computer simulations can (in principle) do more than humans

- Implication:
  - *Constrain* the cognitive architecture
  - Do tasks in a "human way"

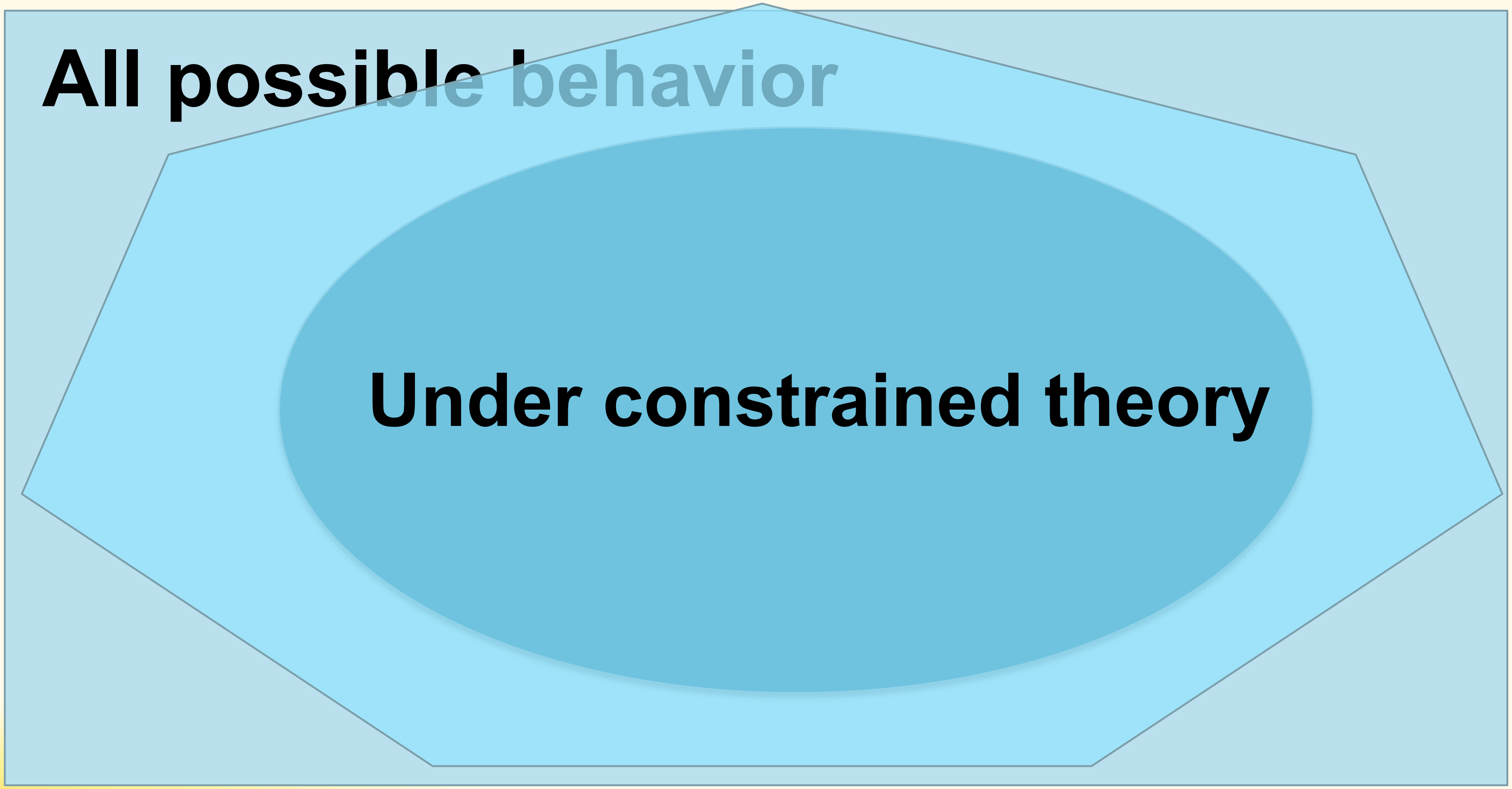
Cognitive architectures vs Turing machine

Cognitive Science style AI:
Understand human by replicating

Engineering :
Develop (more) intelligent systems

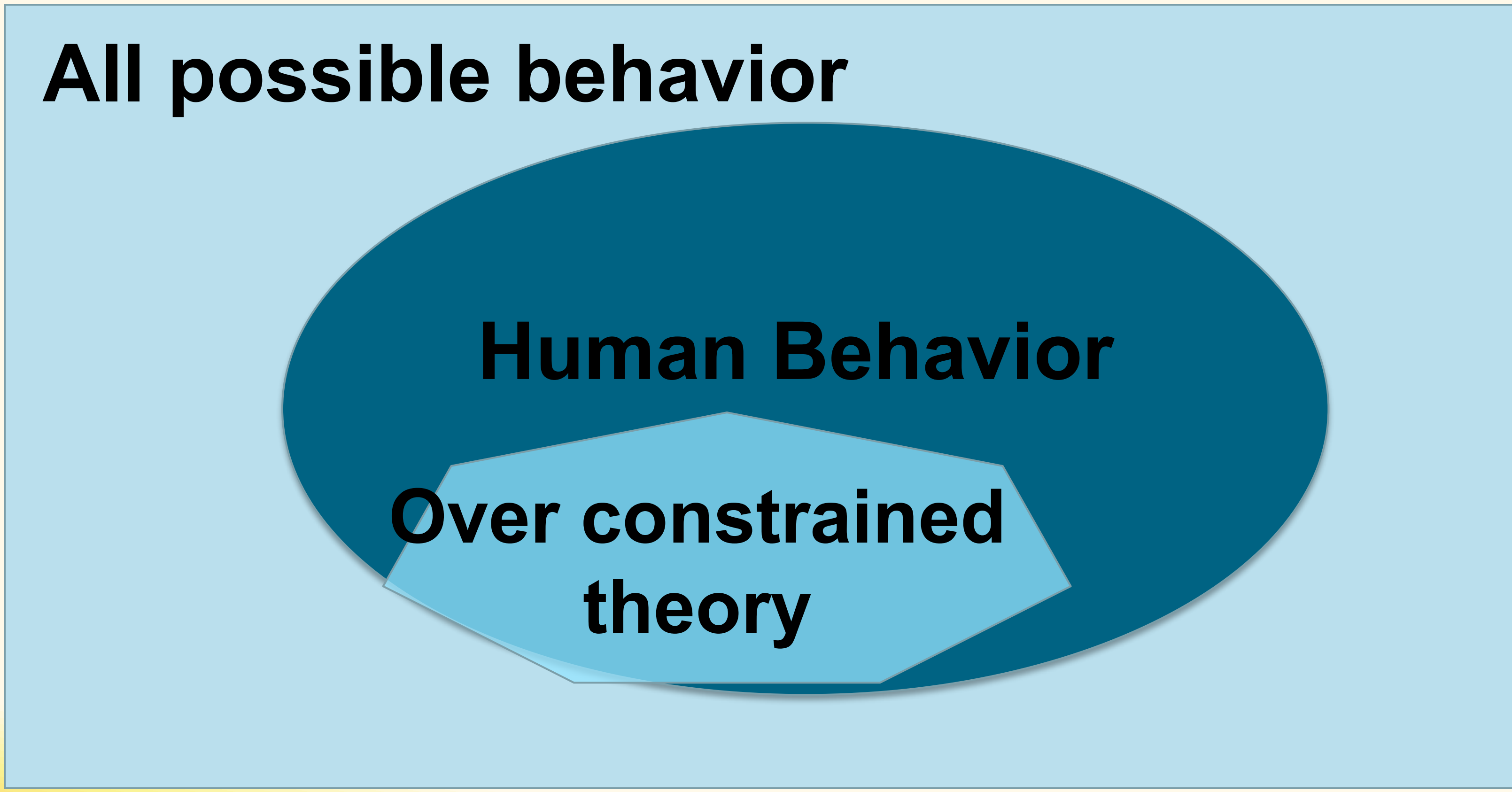
Venn diagrams – revisited

Under constrained model (Turing machine / Mr Data)



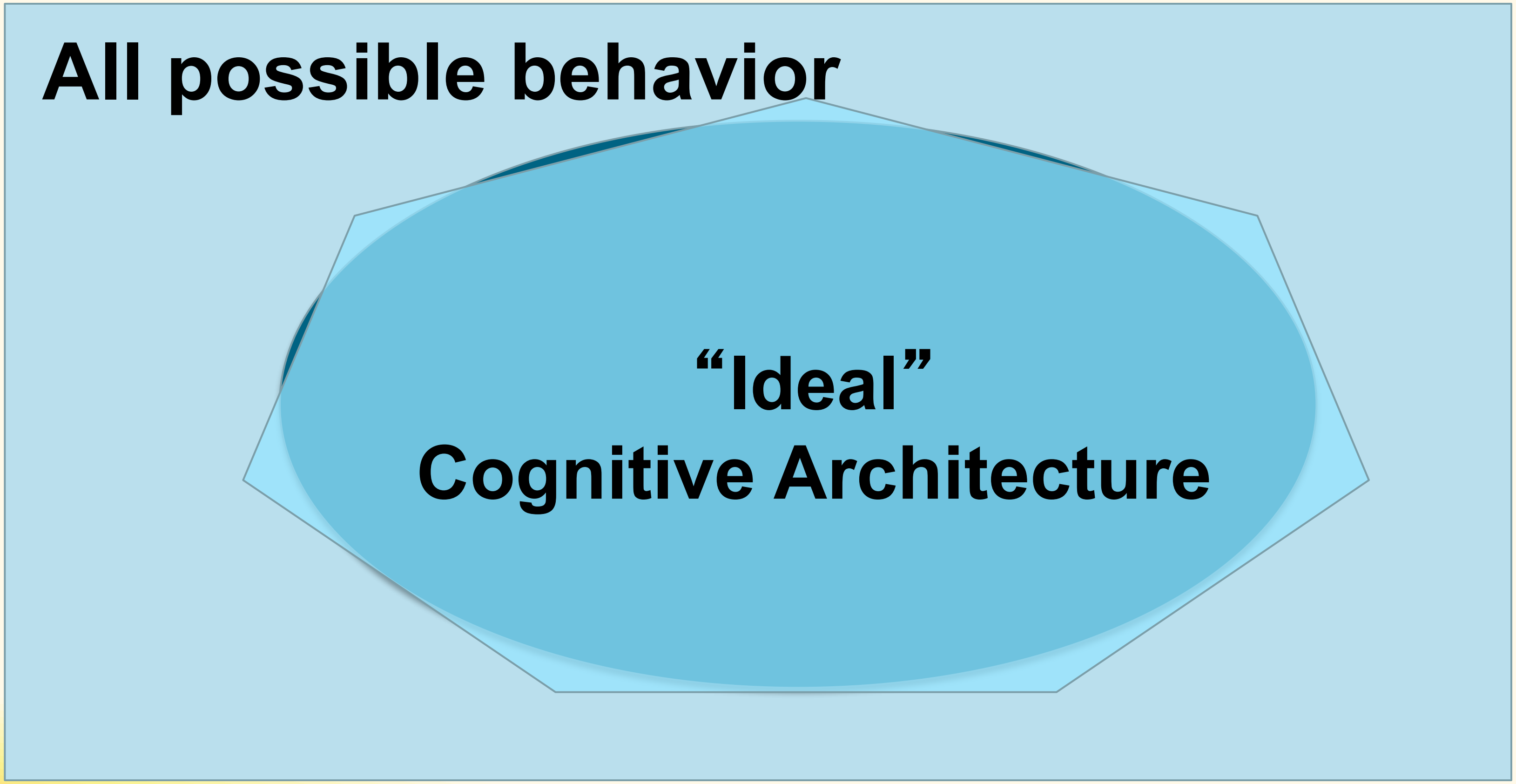
Venn diagrams – revisited

Over constrained model

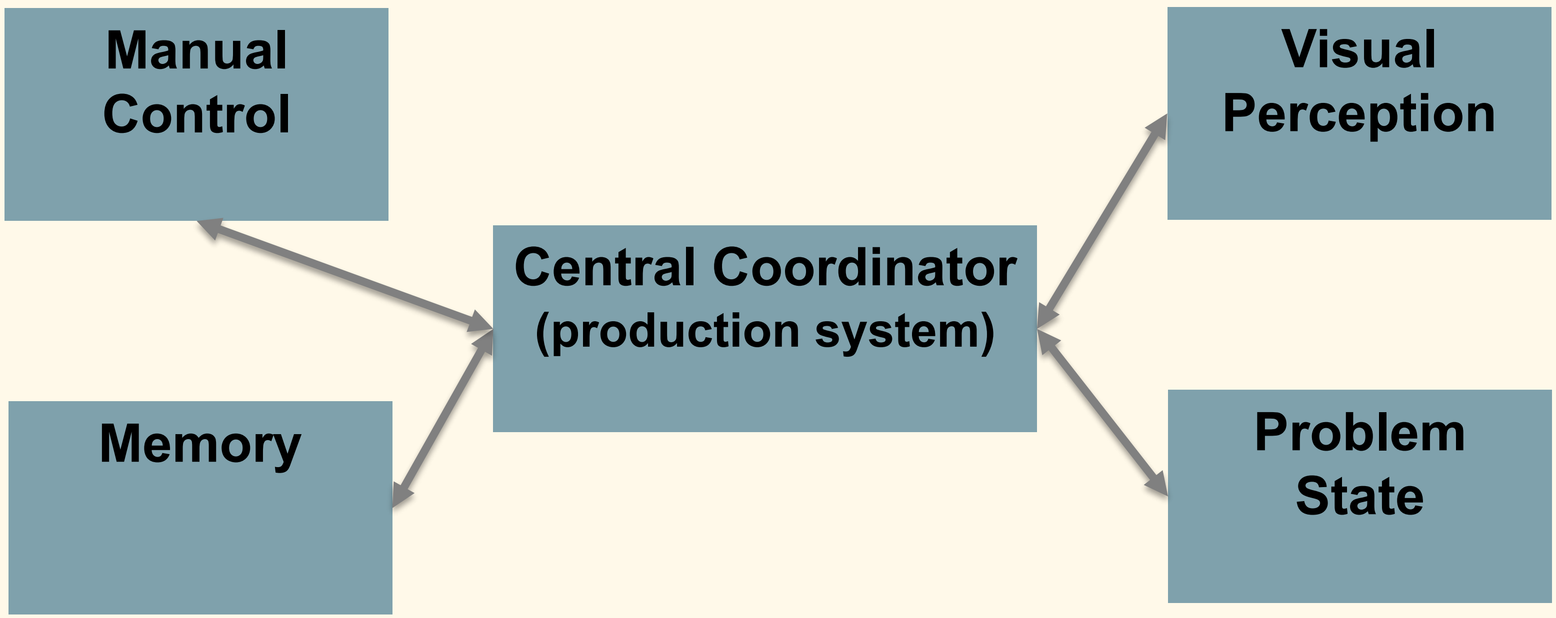


Unified Theory of Cognition

Ideal architecture



Example: Multitasking in ACT-R
(Anderson, 2007; Salvucci & Taatgen, 2011)



One model in cognitive architecture

1. Identify which functions are achieved by the brain/cognition on each time step
2. Specify each process using principles of the architecture
   - Which module executes this process & how?

(exact details left out for now)

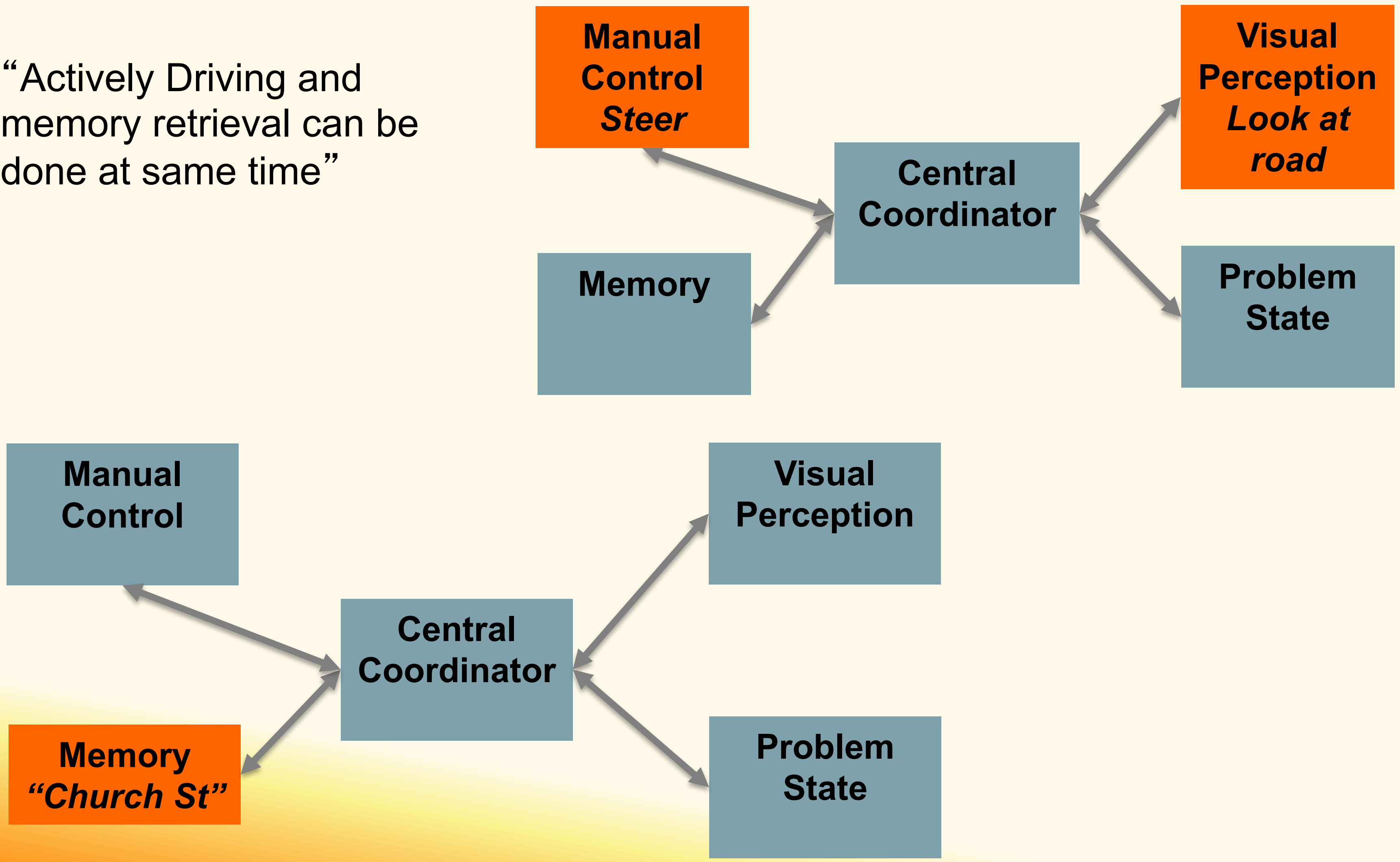
(see appendix for detailed example)

Multitasking in Cognitive Architecture
(Salvucci & Taatgen, 2008, 2011)

- 1 task = 1 cognitive model
- Multitasking =
  executing multiple models “concurrently”
  (or rapid succession)

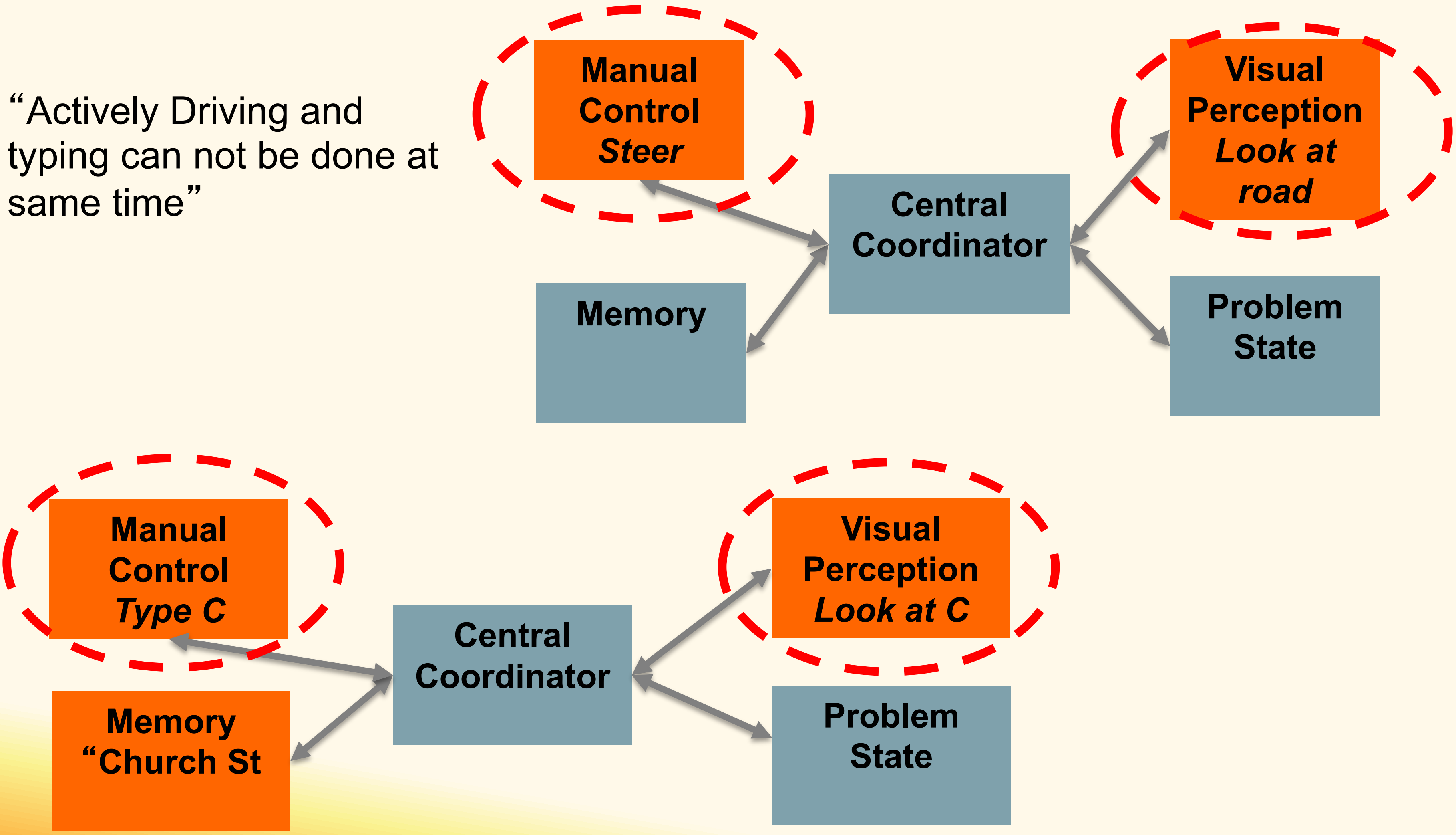
Multitasking: Typing while driving

"Actively Driving and memory retrieval can be done at same time"



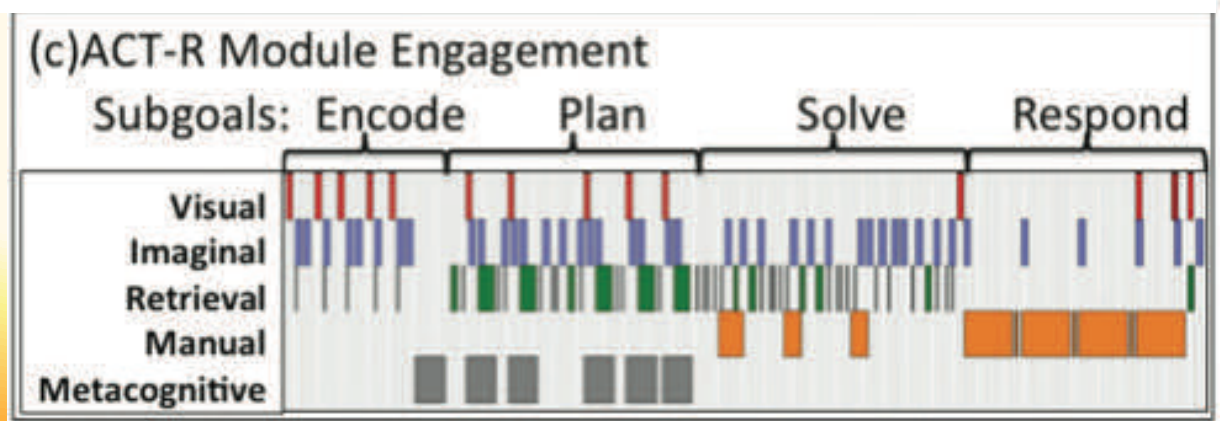
Multitasking: Typing while driving

"Actively Driving and typing can not be done at same time"



Models are not static: Swim lane representation

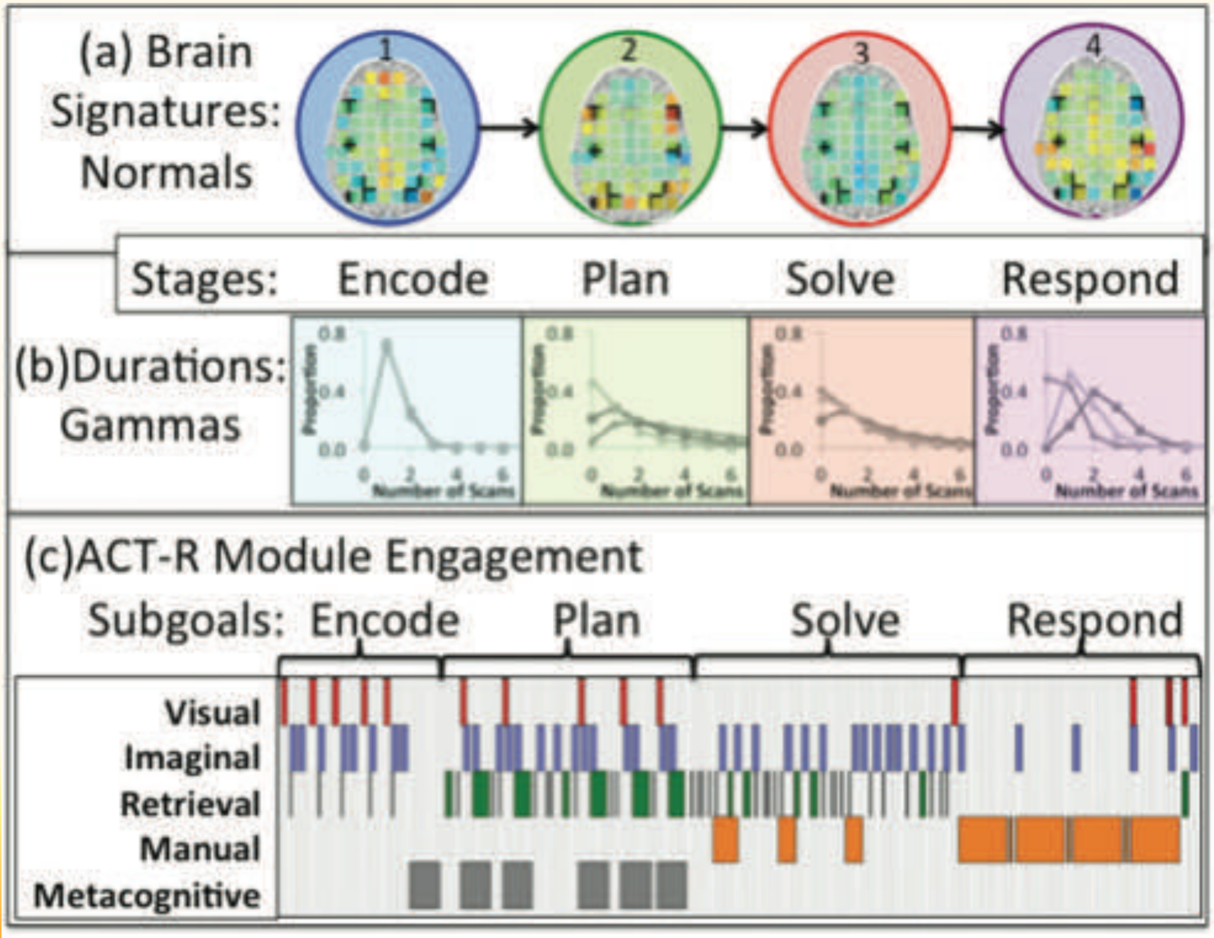
- **Which module is active changes over time**



From: Anderson et al (2016; Psychological Review)

Models are not static: Swim lane representation

- **Which module is active changes over time**



From: Anderson et al (2016; Psychological Review)

Example: Distract-R

See: http://cog.cs.drexel.edu/distract-r/

Advantages cognitive architectures

1. **Formal specification: One framework to describe behavior in multiple settings**
   - Compare: Newton's laws in physics
2. **Working code is detailed**
   - Difficult to be vague/unspecified about aspects
   - Question about the model? Look at the code
3. **Model reuse & predictions**
   - Test in novel settings (e.g., driving on different roads)
   - Multitasking: combine models for various multitasking situations
4. **Understand by building & active testing**

Disadvantages of architectures

1. Requires many details (all modules)
2. Some assumptions are hidden
   – E.g. Default parameter settings
3. Not always clear which component of model is critical/essential for behavior
4. Sometimes models are *too specific* or *not specific enough* for the process that you are interested in
   – e.g., ACT-R misses some details on human vision
5. Falsification is difficult

Today’s topics

- Why use models?
  - In science
  - In practice / industry
- What is a cognitive architecture?
  - What are the (dis-)advantages?
  - What is contrast with cognitive model?
  - Example: multitasking in ACT-R
- **What makes a good model?**
  - **Level of abstraction**
- **If you want to know more…**

Article to read (required for exam)

1. Anderson, J. R. (2002). Spanning seven orders of magnitude: a challenge for cognitive modeling. *Cognitive Science*, *26*(1), 85–112.

Try to get general gist
(study questions provided at end of slide deck)

Abstraction continuum



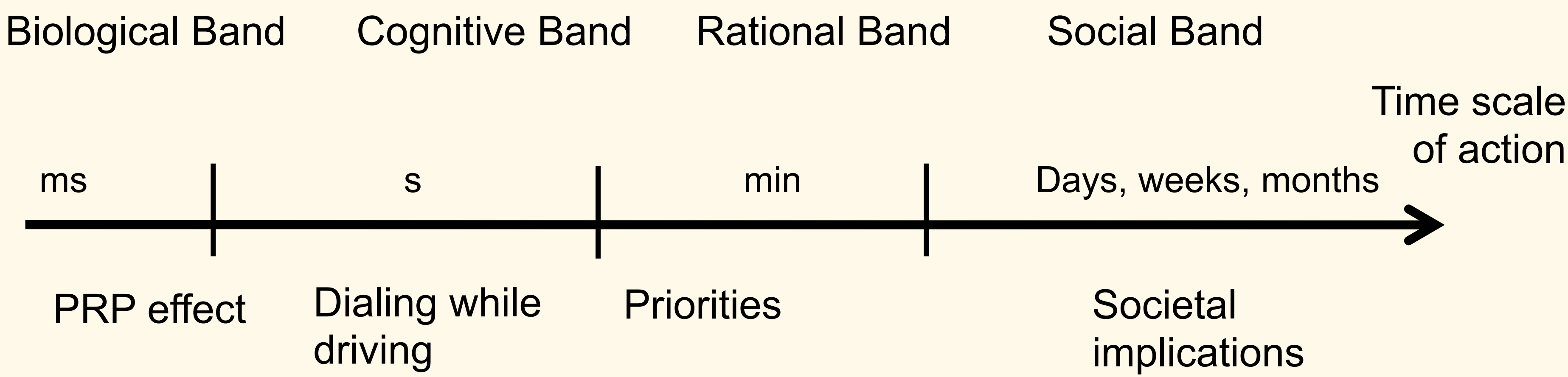
Abstraction continuum

- **Two perspectives:**
  1. **Newell (1990) Unified theories of cognition (discussed in Anderson, 2002)**
  2. **Marr (1982) Vision. Chapter 1 (discussed also in recommended, not required, reading: Cooper & Peebles, 2015) (discussed slightly in appendix for interested student)**

Abstraction continuum (Newell, 1990)

- **In what process are you interested?**
- **What are the steps that are involved in this process over time?**
- ***"Through which lens are you looking"*?**

Abstraction continuum; time scale of action



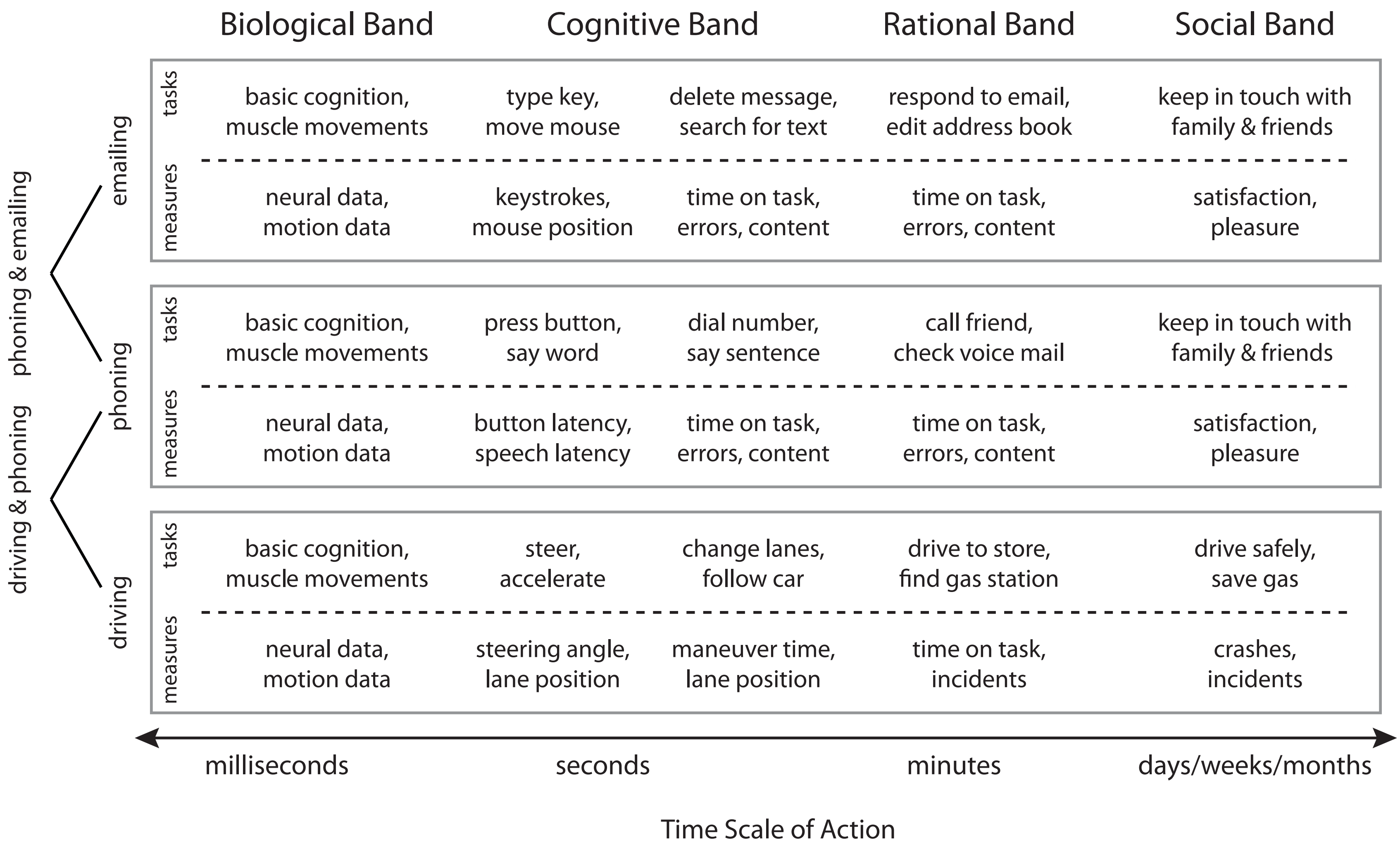


Figure 1.3: The Abstraction Continuum (derived from Newell, 1990).

(From Salvucci & Taatgen (2011) The multitasking mind

Implications of time scale (1)

- **Choice influences:**
  - What you *can* and *should* measure
  - What you should specify in your model
- **Cognitive band: behavioral data**
  - Reaction times, accuracy, choices, eye-gaze (sometimes: fMRI, EEG)
- **Biological band: data for very short time intervals**
  - Eye-gaze, EEG, fMRI, …

Implications of time scale(2)

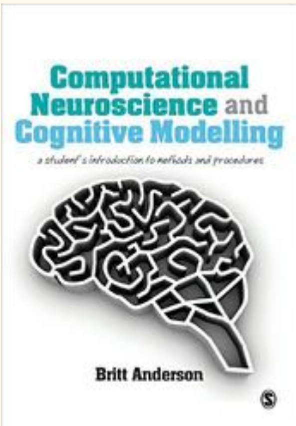
- Abstraction is *always* necessary:
  - Ignore (some parts of) ‘lower’ or ‘higher’ level
  - This makes research powerful:
    - No need to specify irrelevant ‘details’
    - Allows to focus on *relevant* issues
- Issue: what degree of freedom do you take in (under-/over-) specifying a model?
  - Can you defend each of its assumptions?
- For exam: You need to know the levels and their characteristics
  (See appendix of slide deck, articles)
  - Be able to determine what is best level of abstraction for given problem

If you want to know more

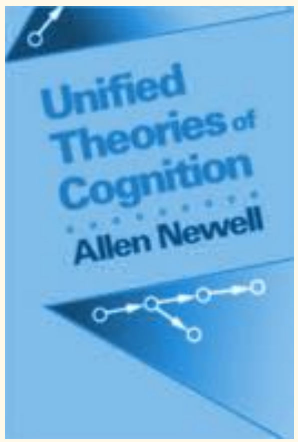
- Cognitive Modeling (INFOMCM): block 2
  - Machine learning — Ben Harvey
  - Processing models — Chris Janssen
  - Bayesian models — Jakub Dotlacil

- Programming: implement & test models in R
- Literature, lectures, poster presentations
- Suitable for students without Psychology degree! (who are interested)
  (in fact: aimed at!)

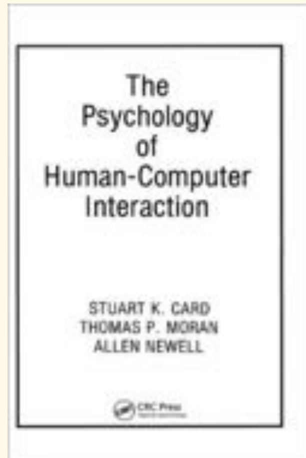
If you want to know more: textbooks



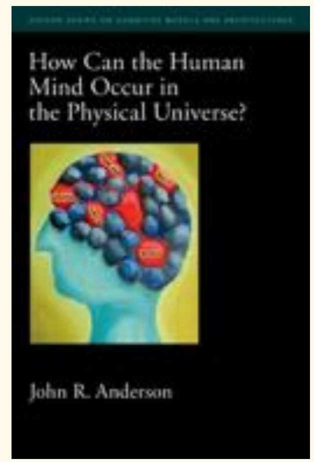
Accessible, general intro on variety of models



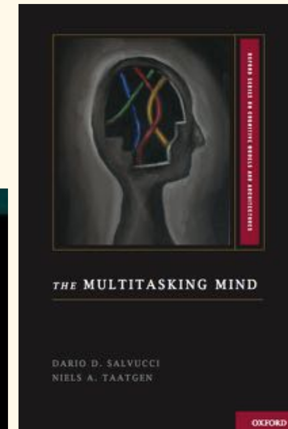
Classic for unified theories



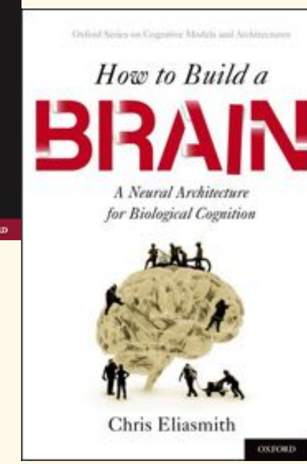
Human-Computer Interaction (older, but brilliant!)



Cognitive Architectures (esp Chapter 1)

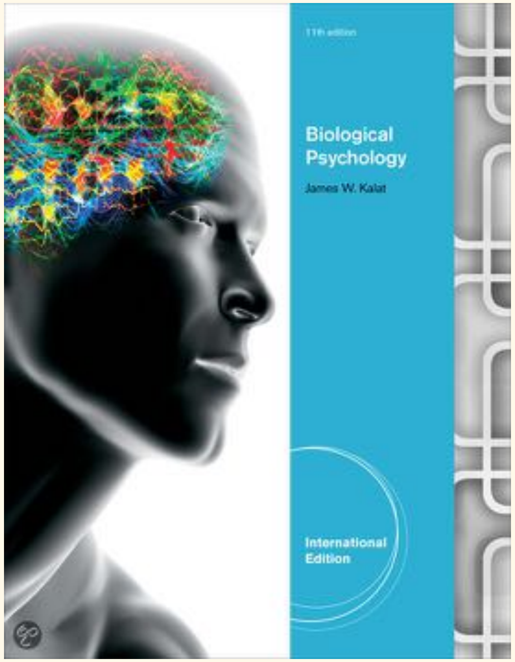


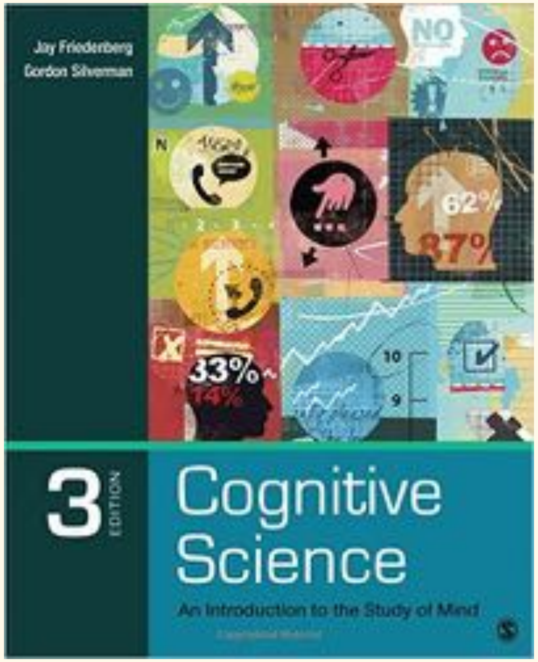
Multitasking (esp C1: abstraction & application)



Neuroscience & Engineering

For more general psych background (not modeling)





- M.S. Gazzaniga, T.F. Heatherton and D.F. Halpern (2011) Psychological Science (4th edition). ISBN 9780393913361. (general overview)
- Kalat (2013). Biological Psychology. 11th edition. ISBN: 9781111839529. (some knowledge of biology is useful)
- Friedenberg, J. & Silverman, G. (2015). Cognitive Science: an introduction to the study of mind (3rdedition). Thousand Oaks, CA.: Sage (more cognitive science / formal → most relevant to AI)

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- If you want to know more…
- *Appendix: more info that is useful for exam!*

Questions?

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Study questions lecture (not bullet proof)

- **What are benefits & disadvantages of using models?**
- **What are the benefits of models for industry/practice?**
- **What is a unified theory of cognition?**
- **What is difference between cognitive model and cognitive architecture?**
- **What is relationship of cognitive models and architectures with strong/weak AI, Turing machine, over & under constrained theory**
- **What are different levels of abstraction, their characteristics, benefits, disadvantages (Newell perspective)**

All questions: Be able to apply these principles/concepts/ideas to case studies

Study questions Anderson (not bullet proof)

- Describe each of Newell's 4 bands. How do they relate to time units and systems?
- What is the decomposition thesis?
- What is the relevance thesis?
- What is the modeling thesis?
- Why is the "unit-task" level useful for each thesis?

All questions: Be able to apply these principles/concepts/ideas to case studies

Example exam questions from previous years

Some notes on these questions:

- The following questions were asked in previous years. They vary in their difficulty. Some focus on the lecture content, others on your understanding of the articles.
- Some stay close to study questions that I gave with my classes (see previous slides), others ask you to apply your knowledge to a novel situation

Example exam questions from previous years (1)

Give two general benefits of using computer models / simulations (cognitive models) to study human behavior and cognition *for science* (no detailed explanation necessary).

Example exam questions from previous years (2)

One application area of cognitive models is in the form of “intelligent tutoring systems”, which were discussed in class and in the paper by Anderson. Explain *briefly* why a cognitive model is useful for an intelligent tutor system that teaches math (for example, a system that tutors students on solving equations like “2x + 7 = 27”).

Example exam questions from previous years (3)

Consider this case study: A researcher wants to build an “intelligent e-mail notification system”. This system dynamically tracks how “busy” a person is using a cognitive model. Based on the model, the system finds opportune moments to notify the person of incoming e-mails. For example, only when the person is judged to be not too busy (an example would be when they are checking Facebook).

The researcher tests the system with a pilot dataset of 20 users that perform various tasks on the computer such as inserting data in a spreadsheet, typing e-mails, and checking facebook. She wants to find the most opportune moments to notify the user of e-mails in the future. The researcher has access to the following data (all measured in 20 milliseconds accuracy):

- what tasks the person/user works on when
- eye-movement data: where do they look when?
- mouse clicks: what do they click when?
- key presses: what do they type when?

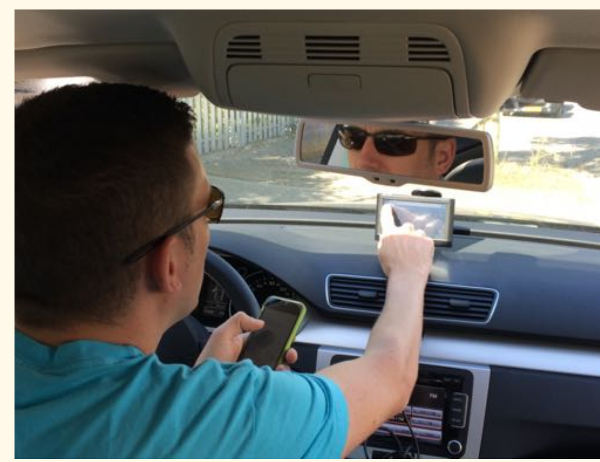
Explain **which of** ***Newell's*** **bands is most appropriate to model human behavior for this situation**

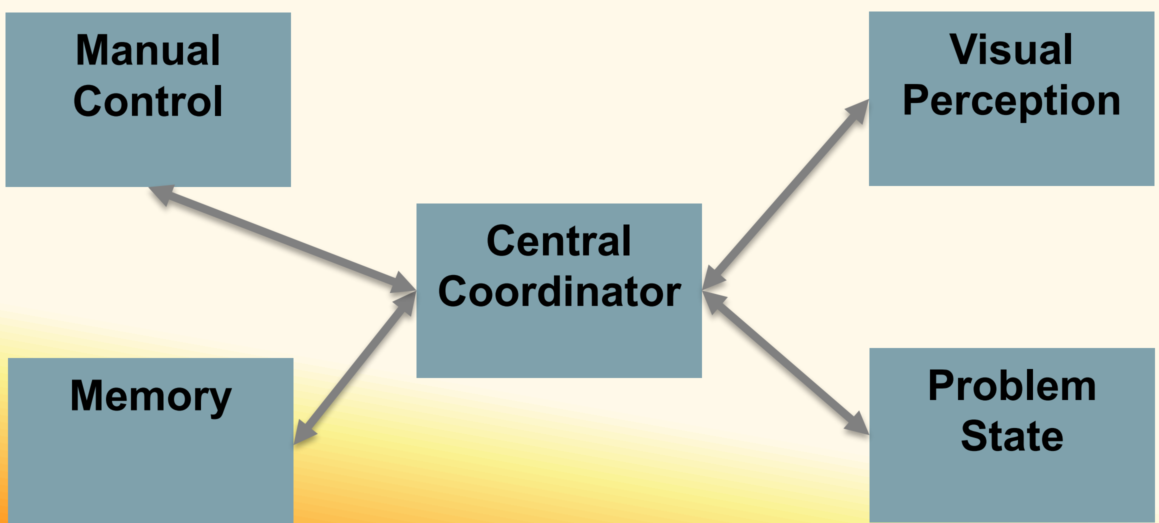
Additional slides

- **ACT-R process model over time**

Example 1: Type in address

- **Which functions are achieved & by which module?**





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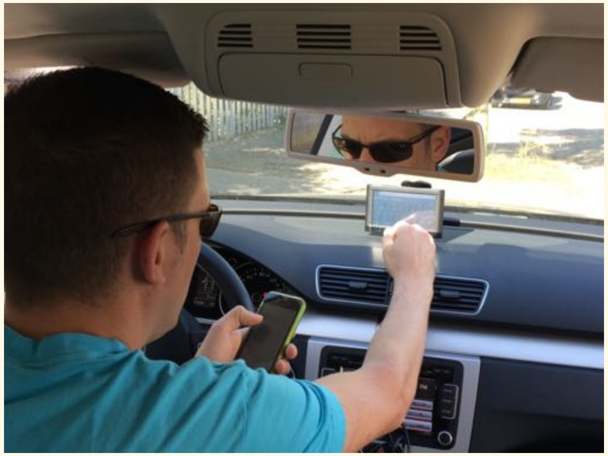

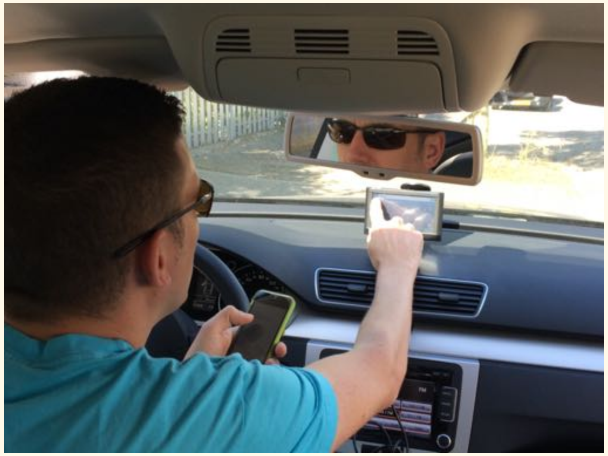

Executed *functions*:

- Look at the phone for address (vision)
- Look at sat-nav (vision)
- Store address in memory (memory)
- Type address (motor)
- Remember where you are (problem state)
- Execute actions in the right order (central coordinator)

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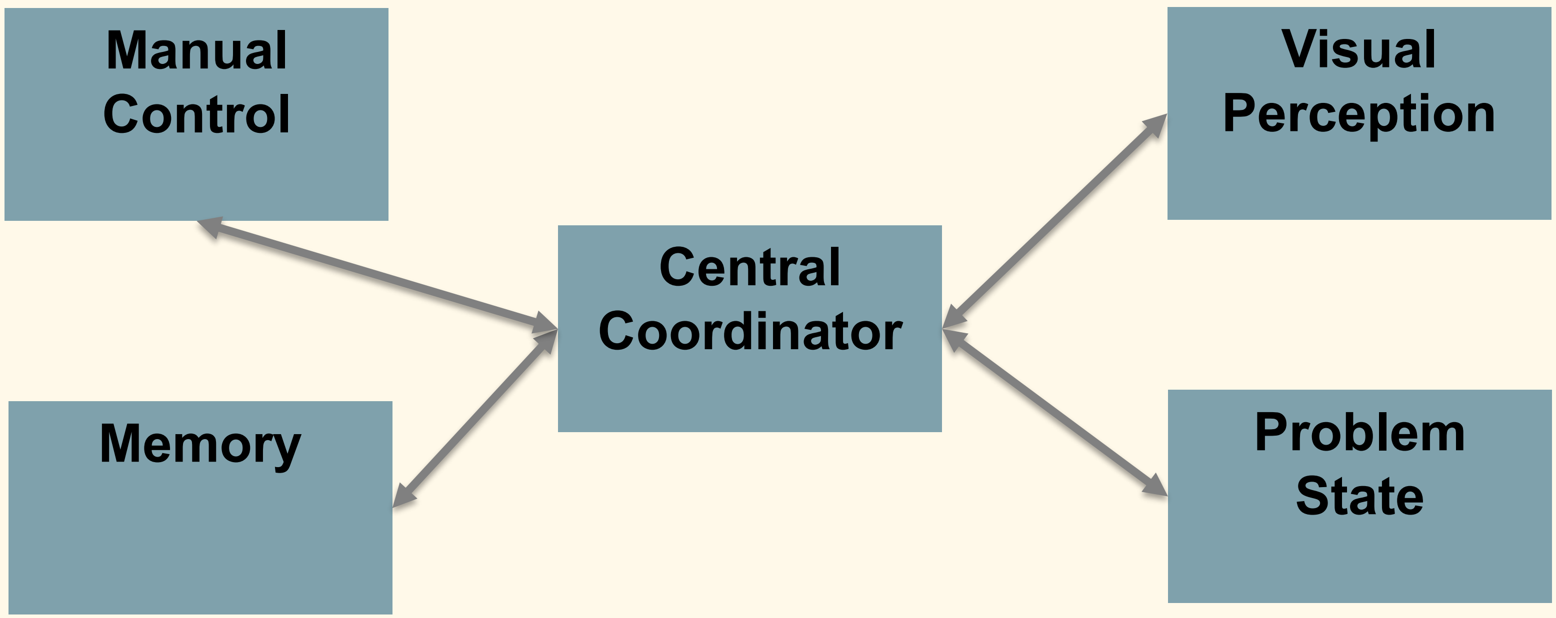

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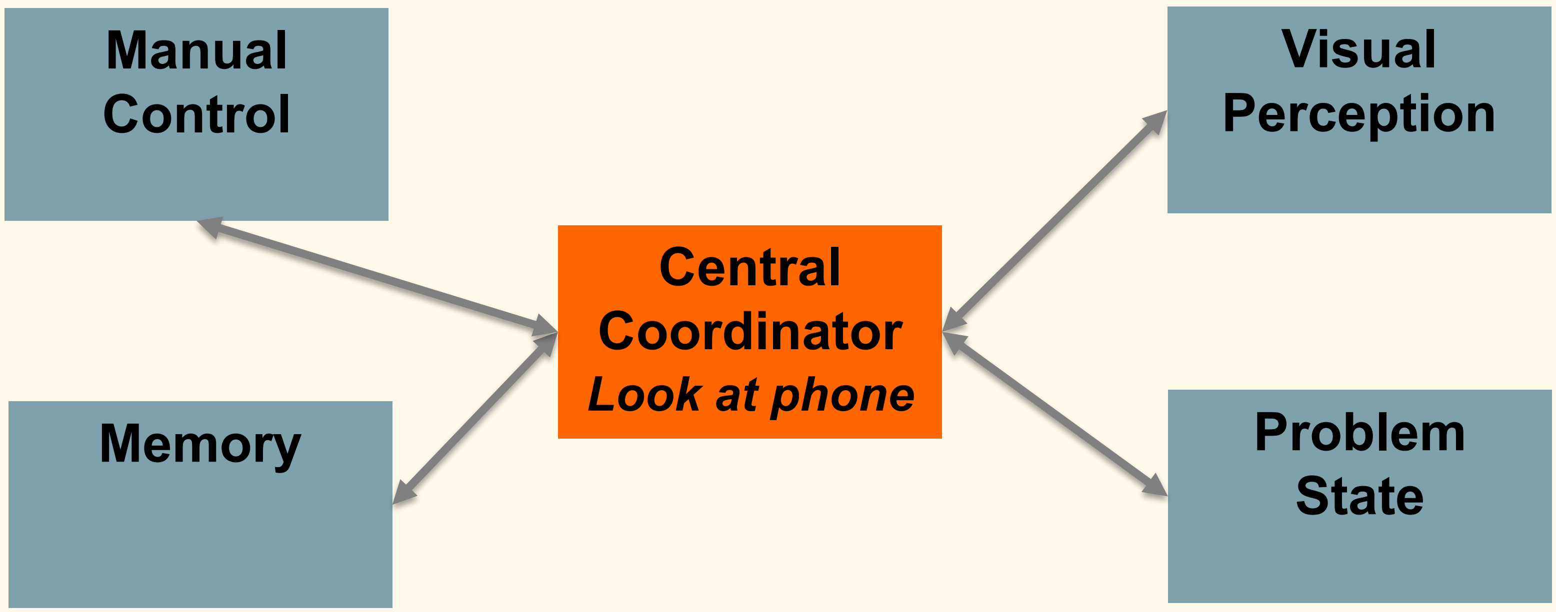

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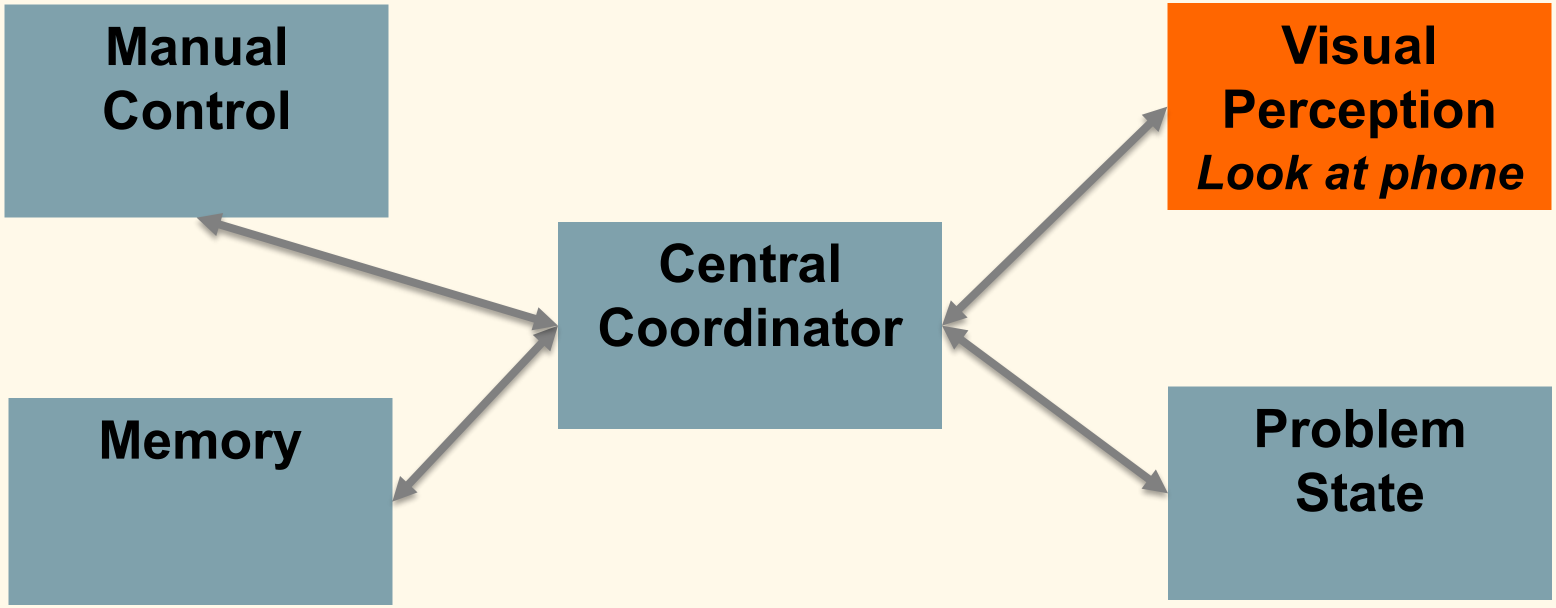

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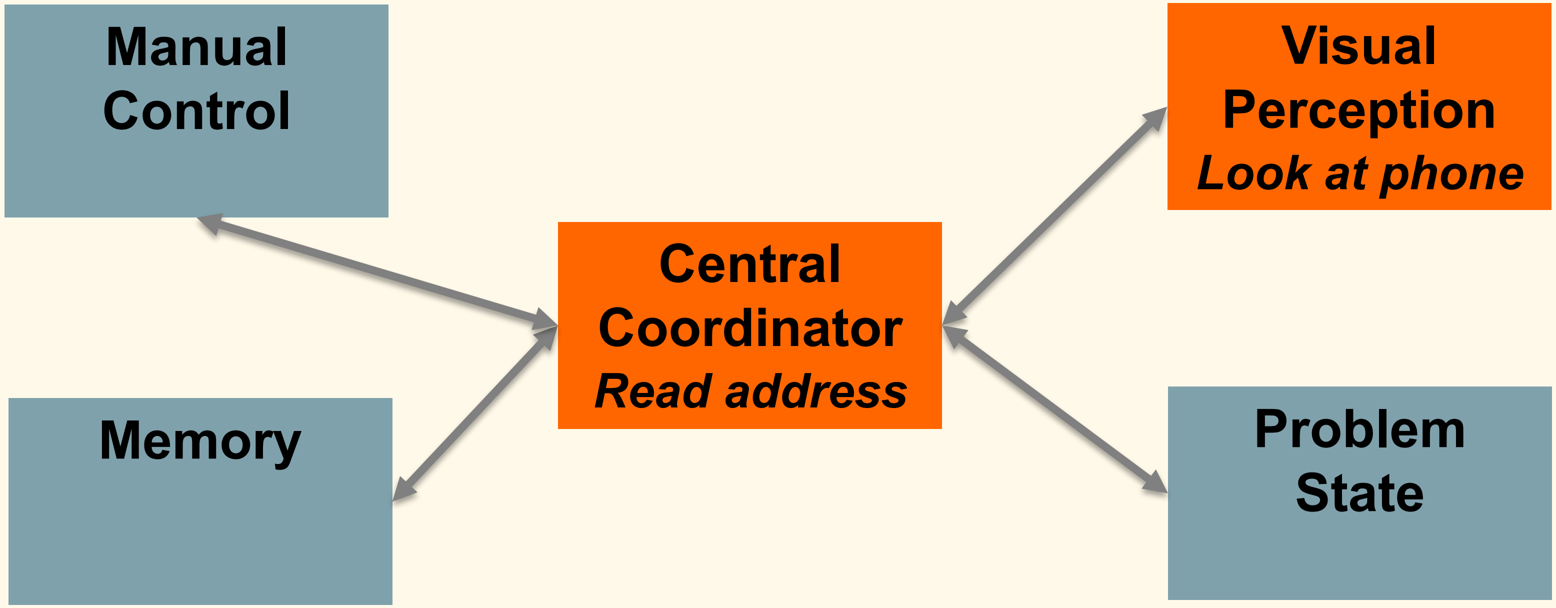

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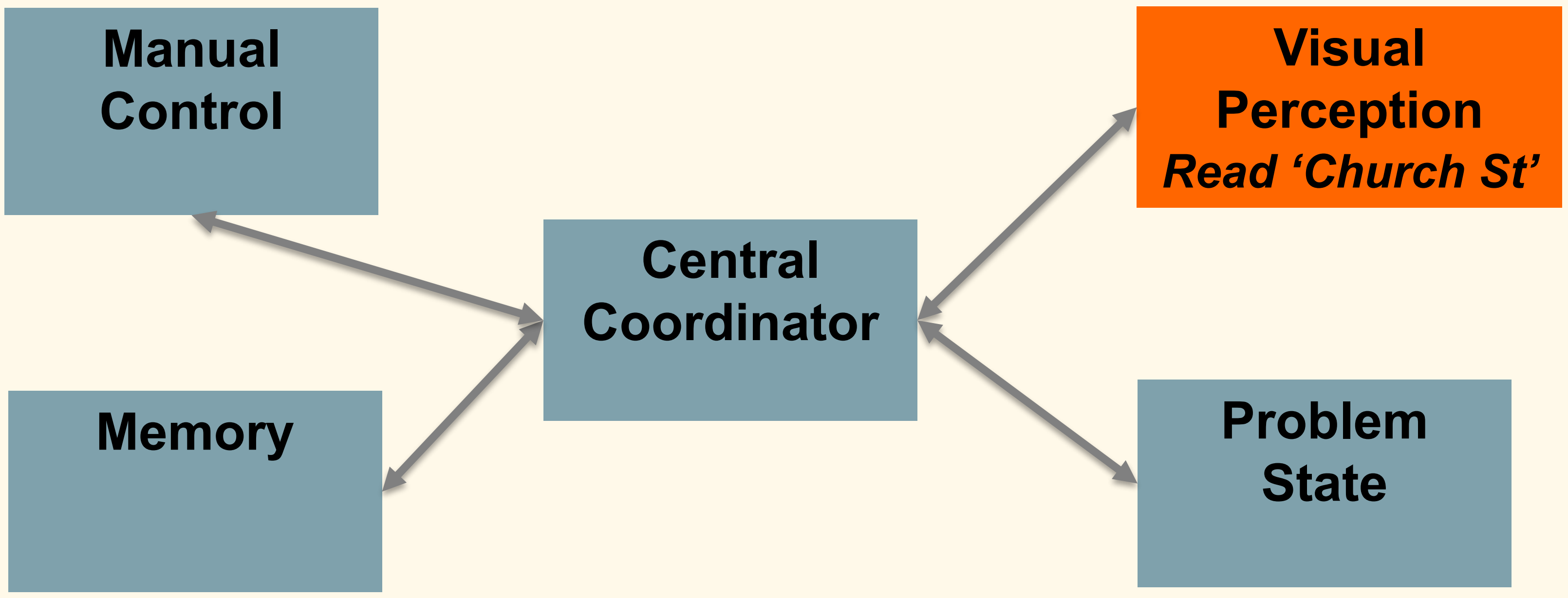

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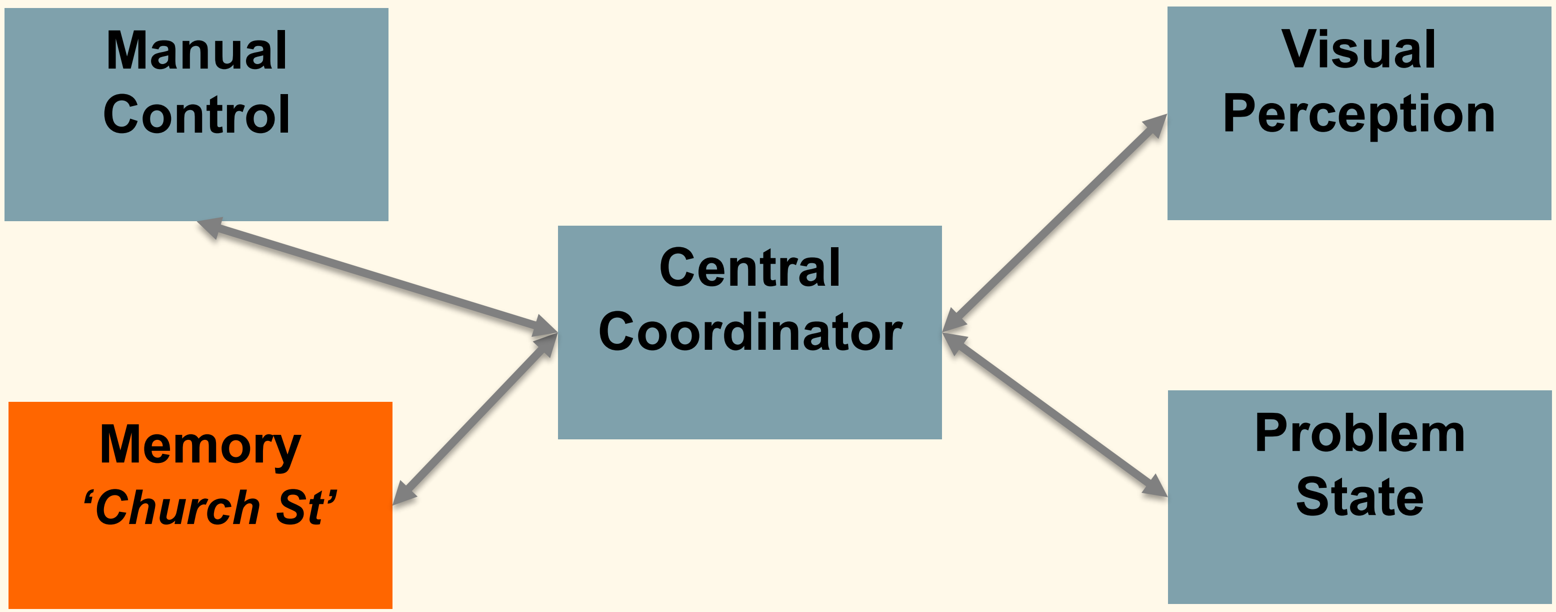

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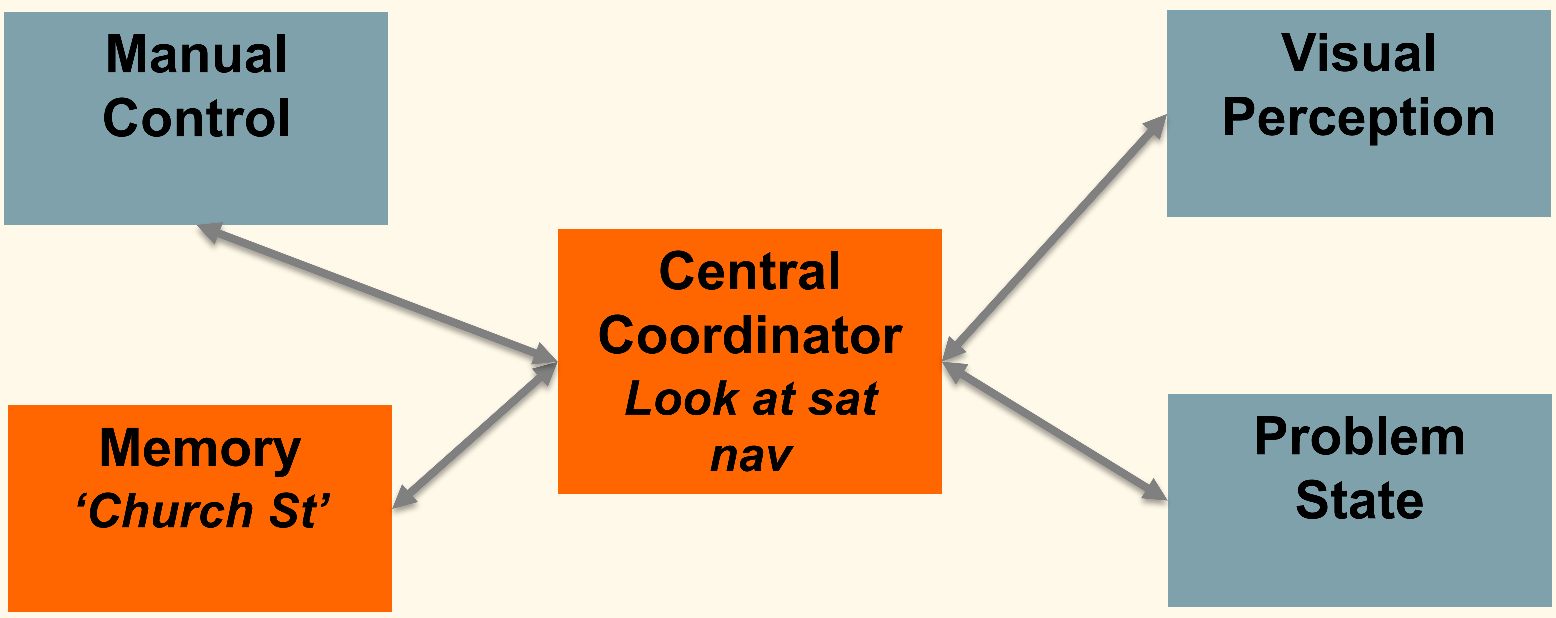

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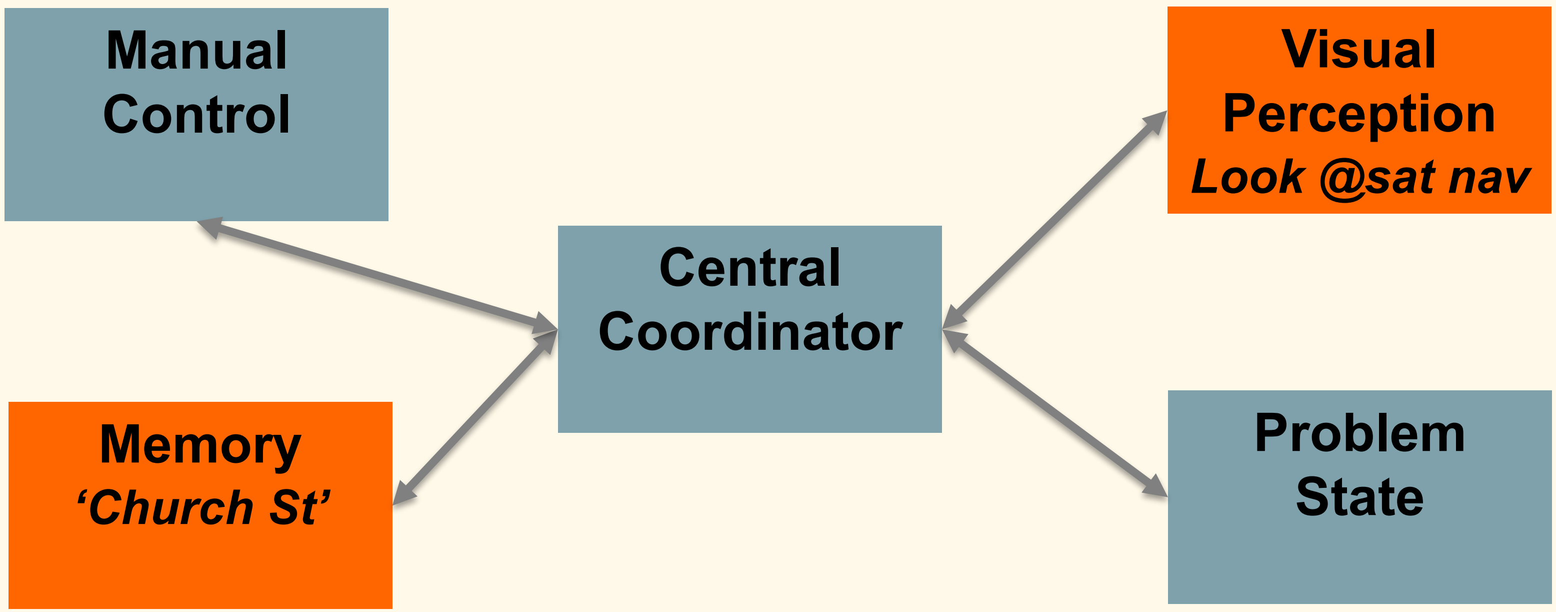

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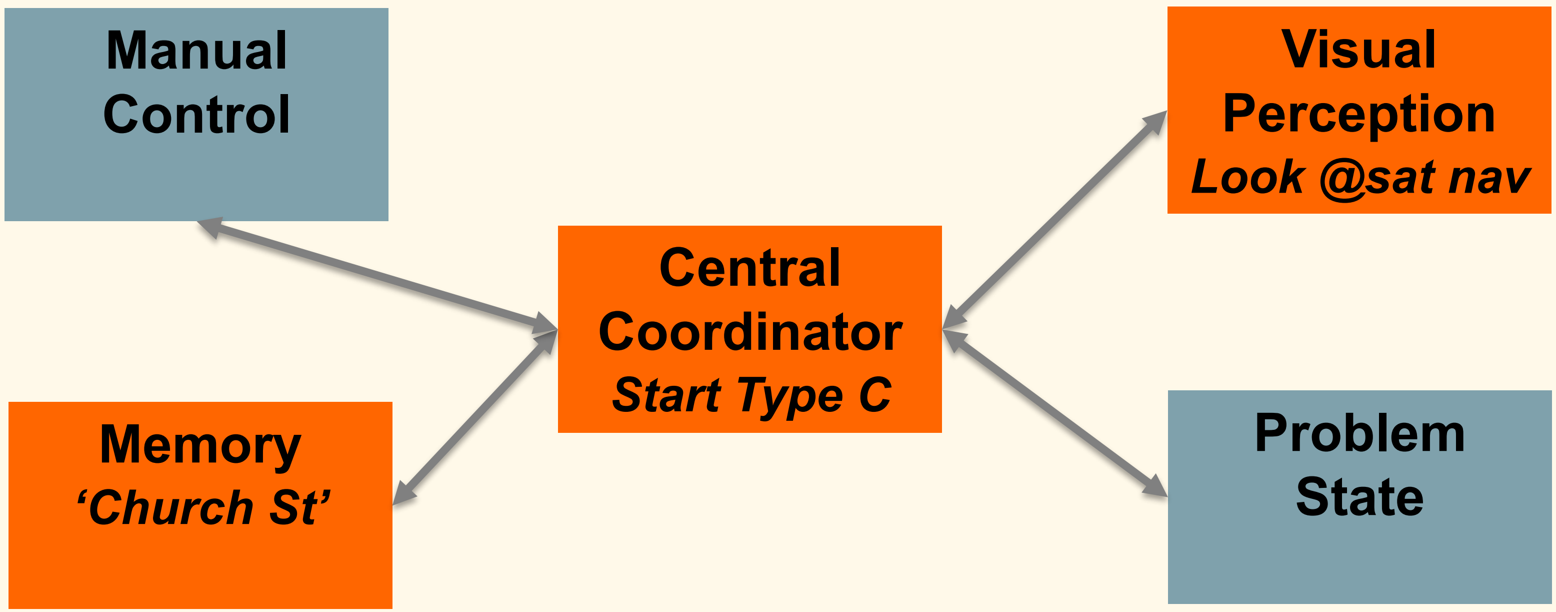

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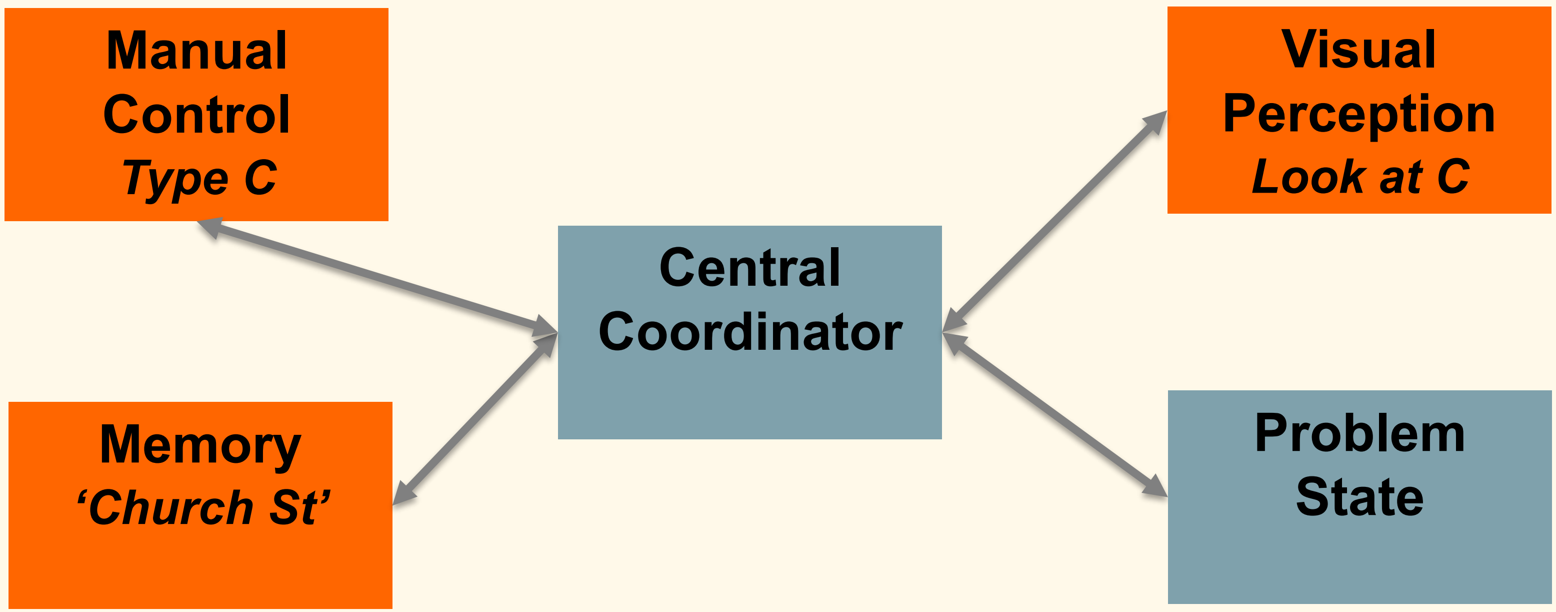

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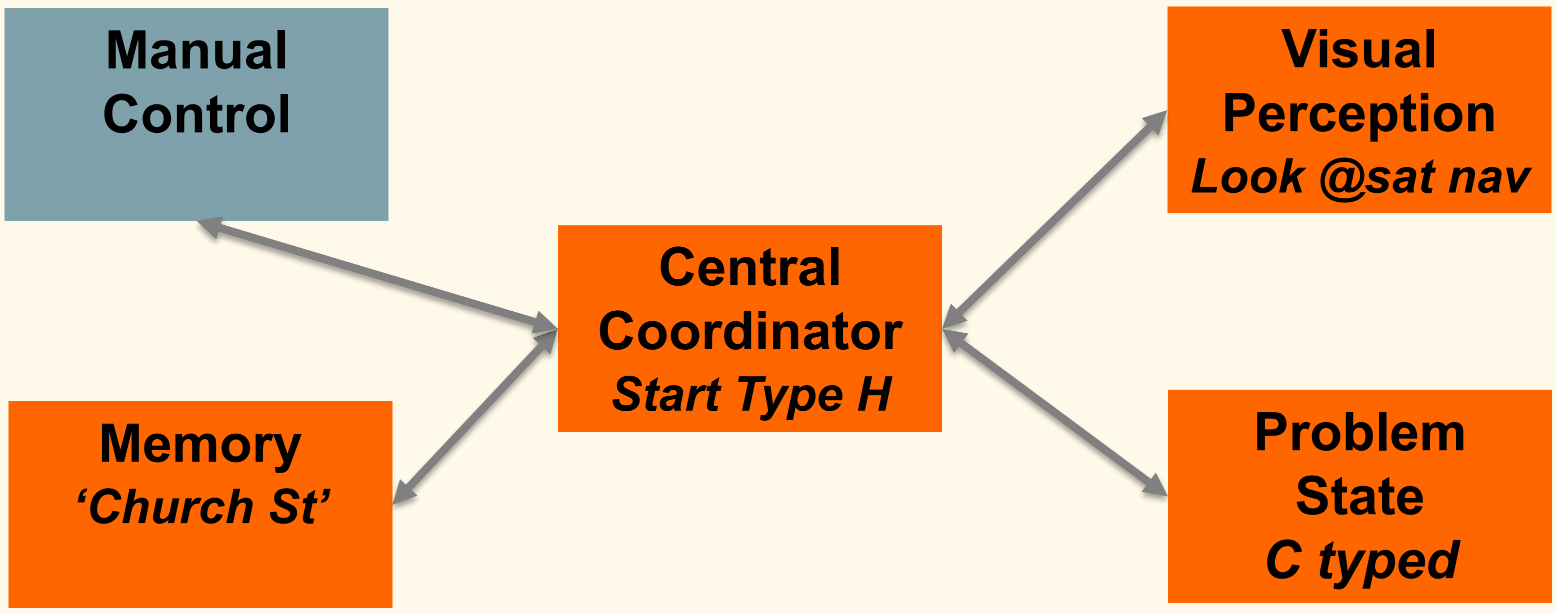

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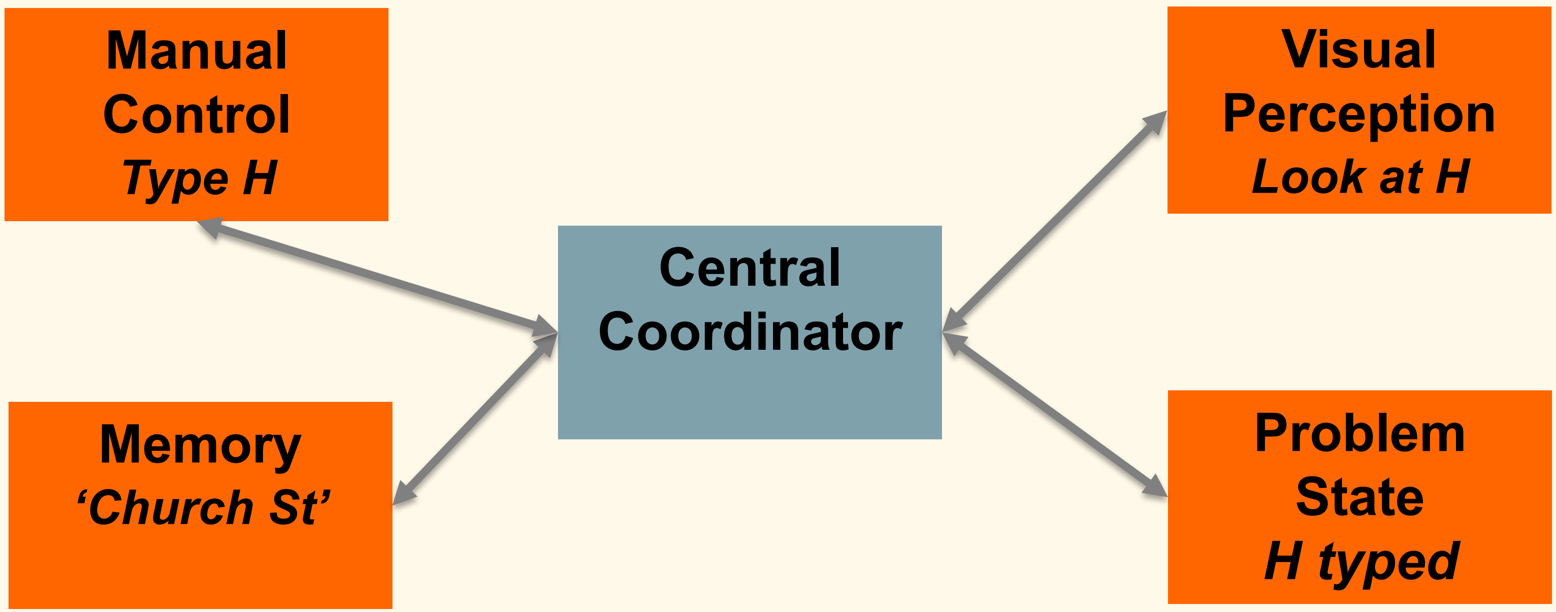

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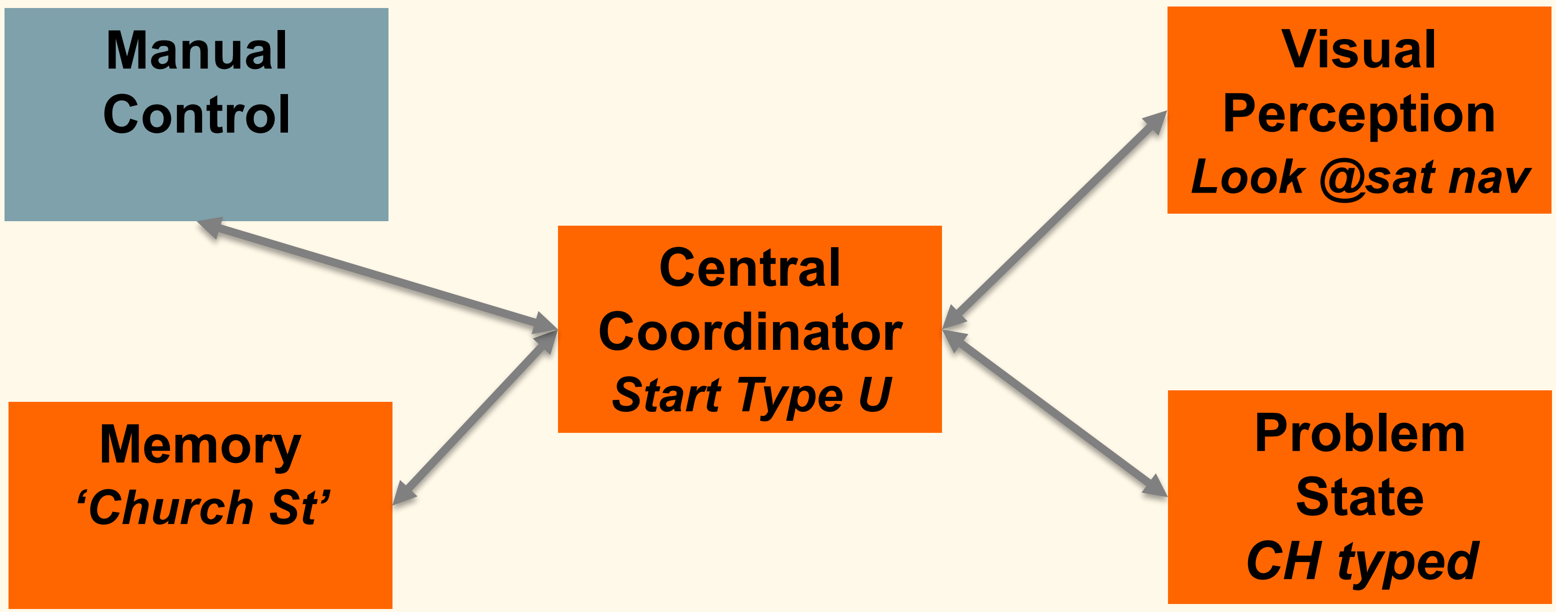
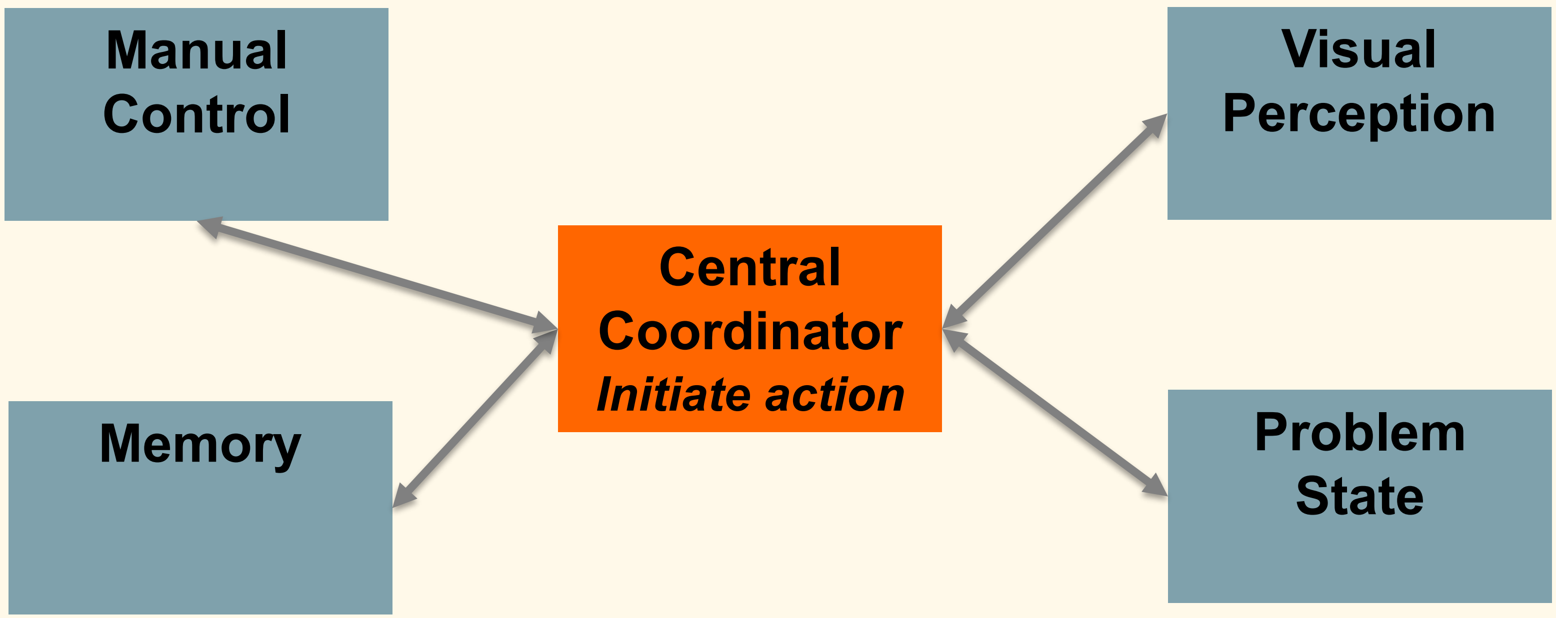


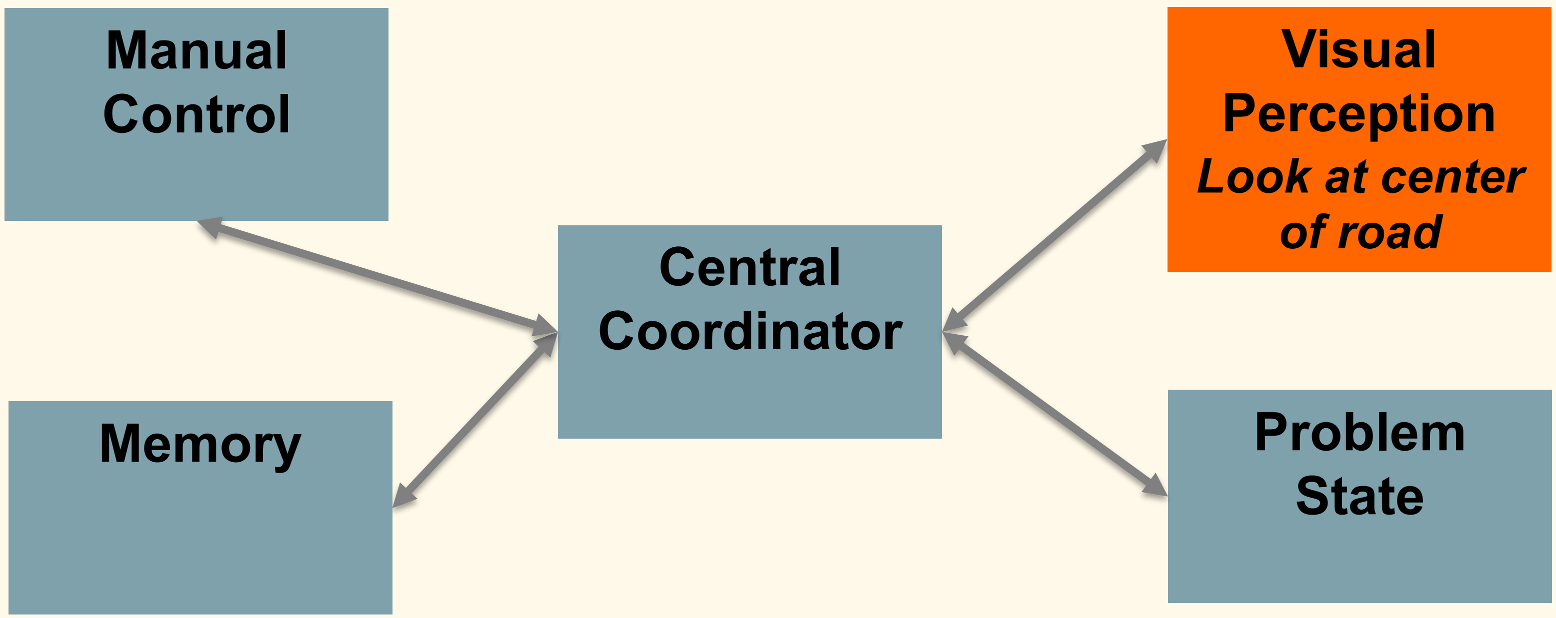
Example 2: Drive simulated car

- Executed *functions*:
  - Look at road (vision)
  - Identify center of road (vision)
  - Determine distance to center (“Black box”)
  - Use steering wheel to improve lateral position (manual)

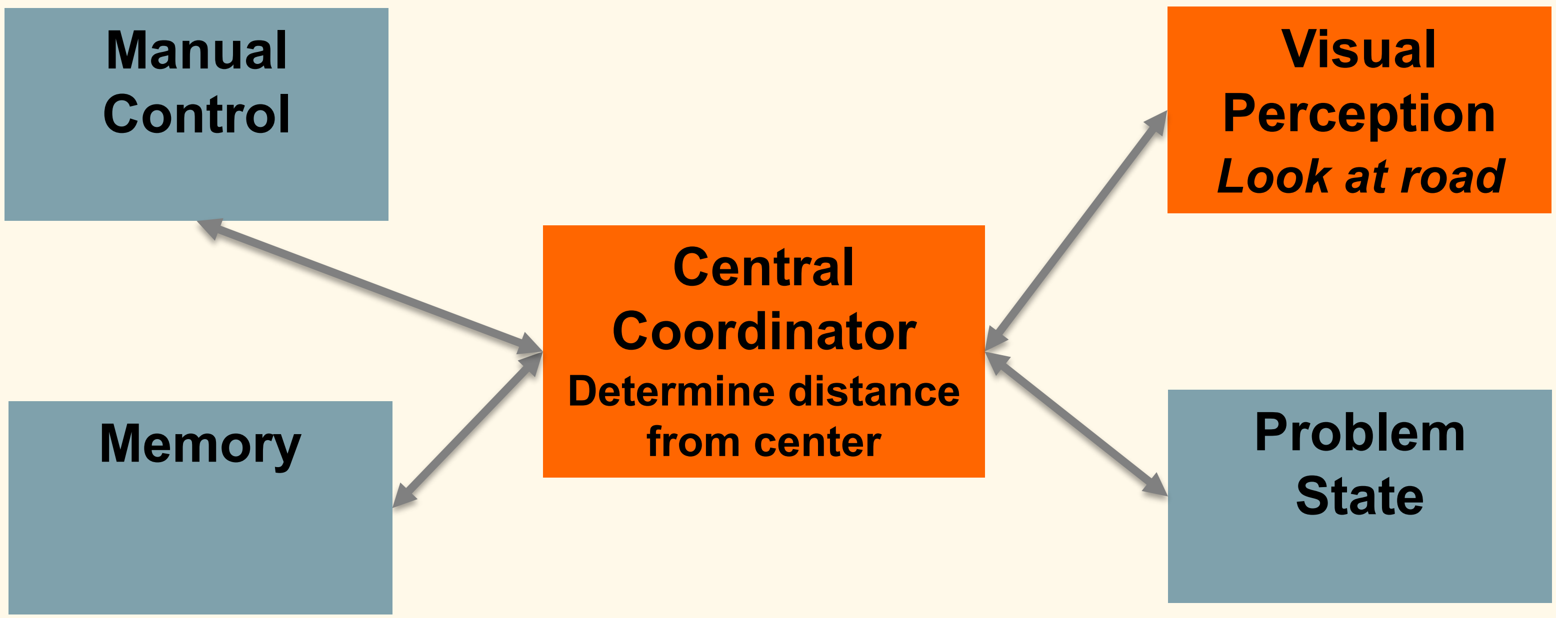
Simulated driving



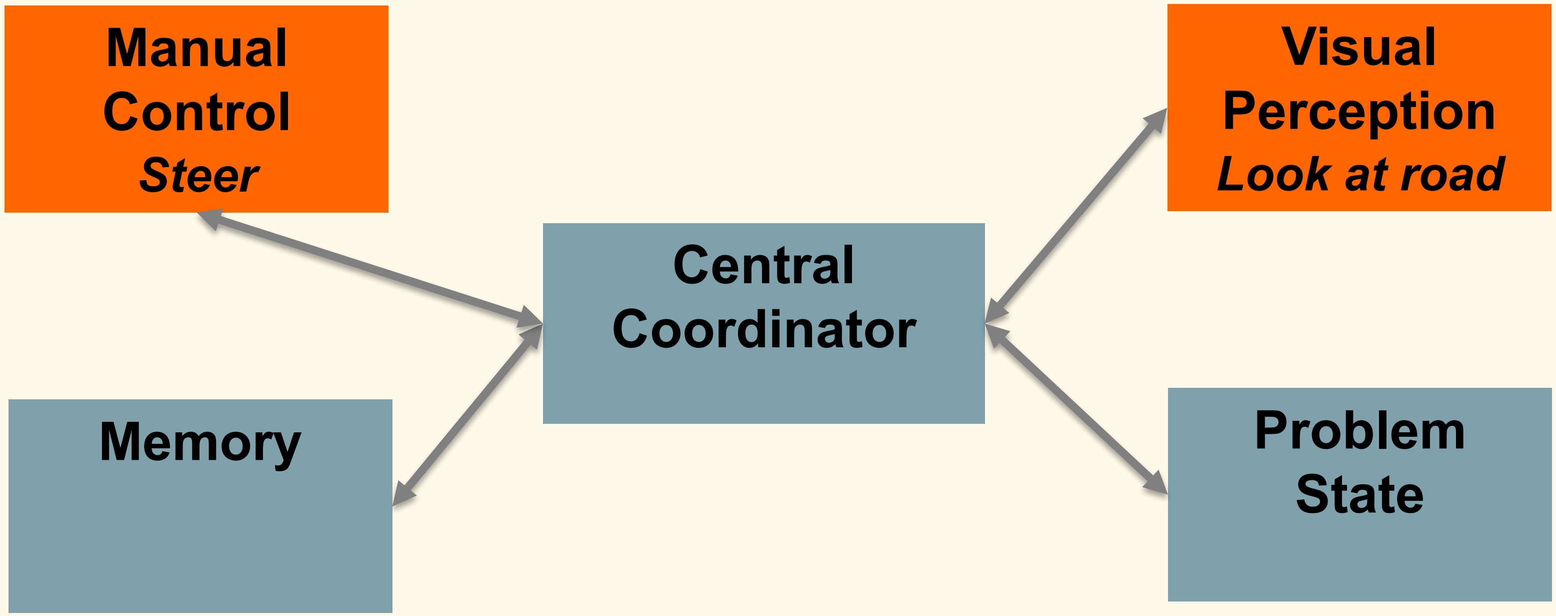
Simulated driving



Simulated driving



Simulated driving

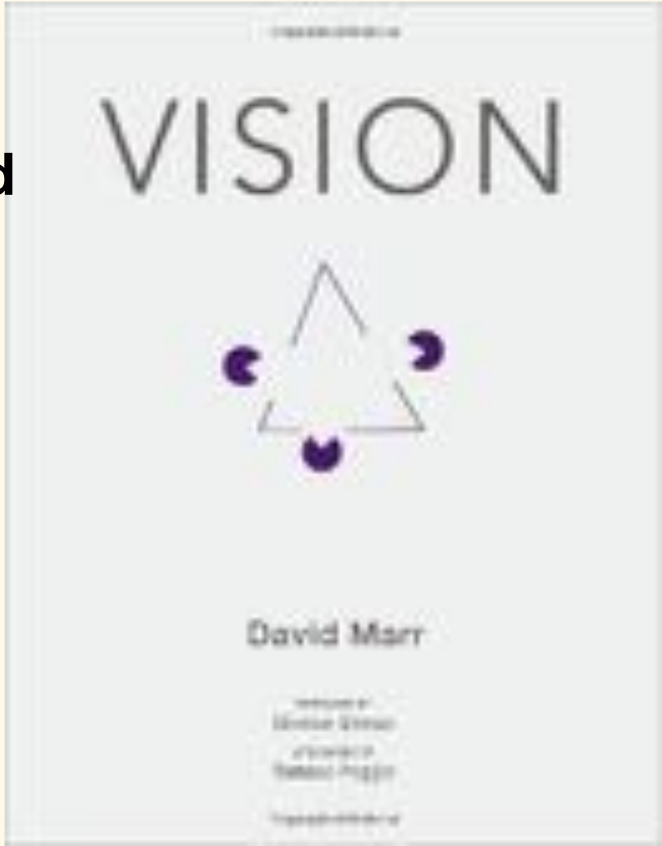


Additional slides: Levels (this time Marr)

Abstraction continuum

- **Alternative view:**
  David Marr (1982) Vision Chapter 1
- **3 levels:**
  - Computational theory
  - Algorithmic theory
  - Implementation theory

More detailed

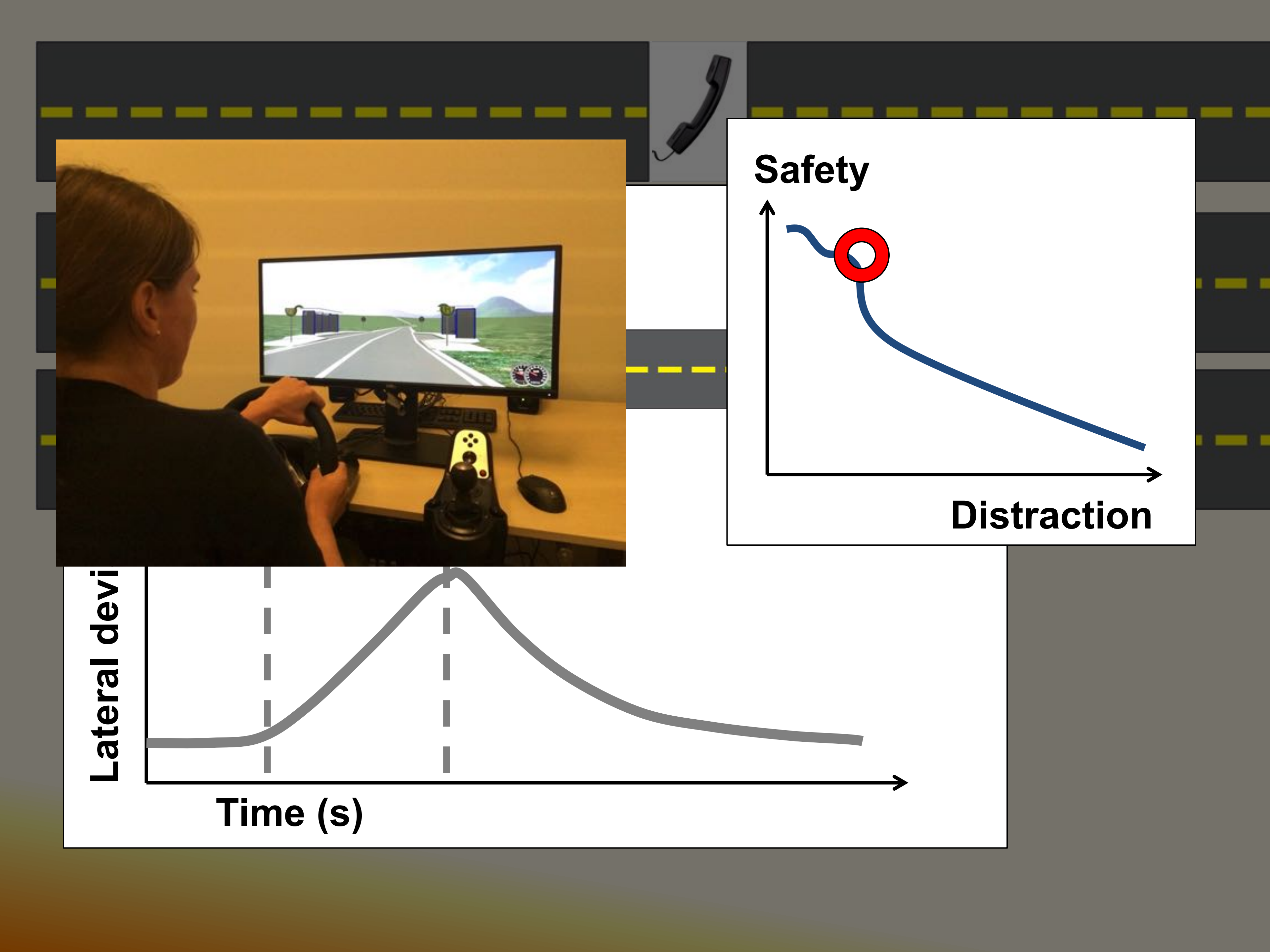


- **Each level is important**
- **Each level explains *different* aspects of behavior**

Marr: Computational level

- Goal
  "*WHY* do we do what we do"?
- What they do not answer:
  - What is done? What strategies are used? (algorithmic)
  - How does brain/neurons achieve this? (implementation)
- Common characteristics:
  - Small set of equations explains behavior
  - Explanation involves characteristics of statistics of the environment (e.g., adaptive argument)

Example: Computational level (with algorithmic flavor)


Safety
Distraction
Lateral devi
Time (s)

See also video clip of example (computational model with algorithmic flavor)

https://youtu.be/rQhj0vjVZFU

Marr: Algorithmic level

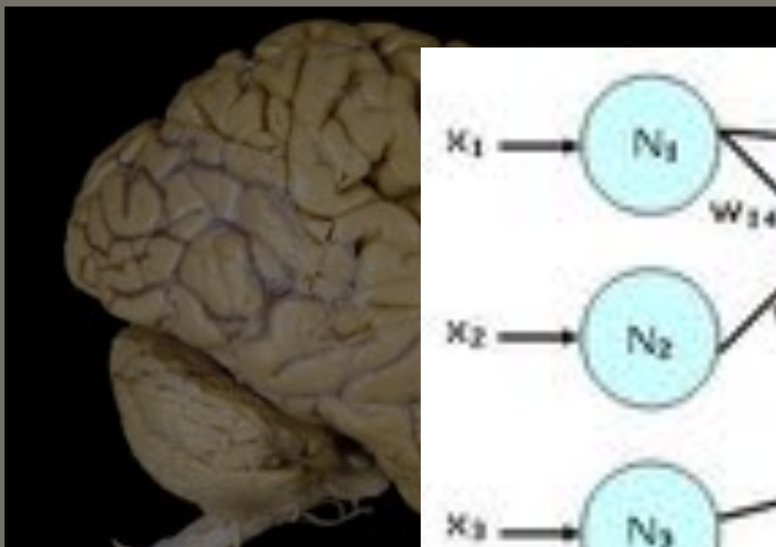
- Goal :
  - How is a computational theory implemented?
  - What is the “input”, what is “output”
  - What type of algorithm/strategy solves this problem?
- What they do not answer:
  - *Why* is implementation like this? What is purpose (computational)
  - What is physical implementation? How brain achieves this (implementation)
- Common characteristics:
  - Detailed algorithms
  - That describe aspects of the process

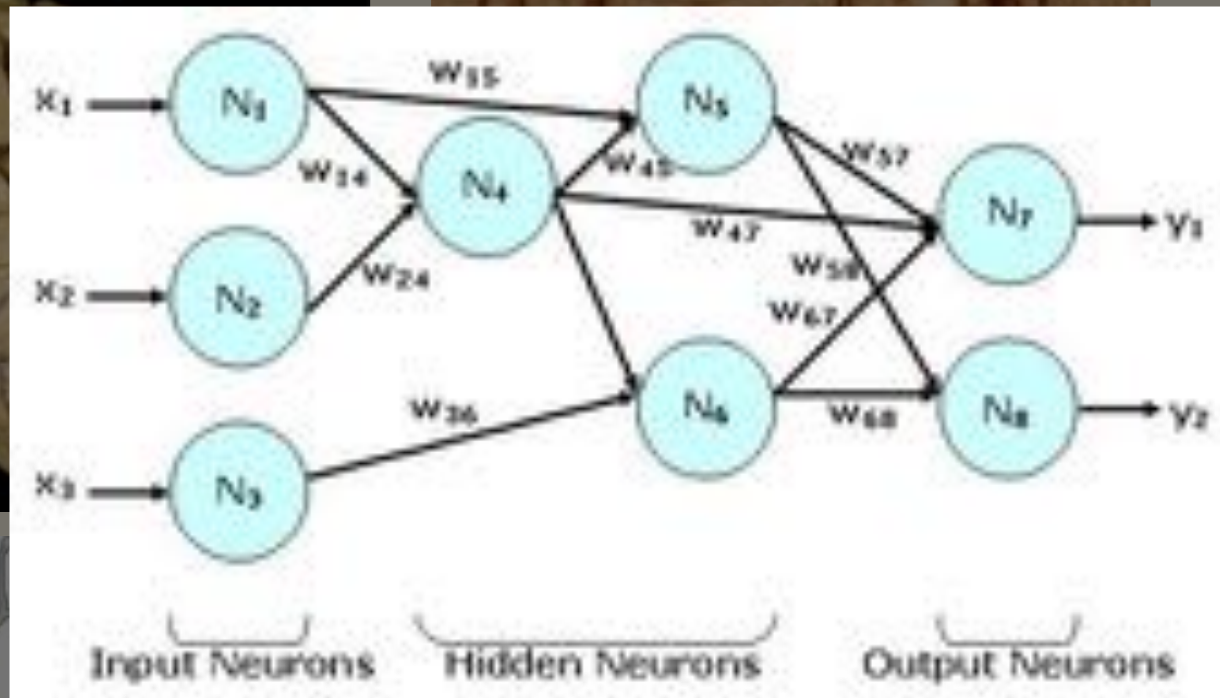
Example: Algorithmic level

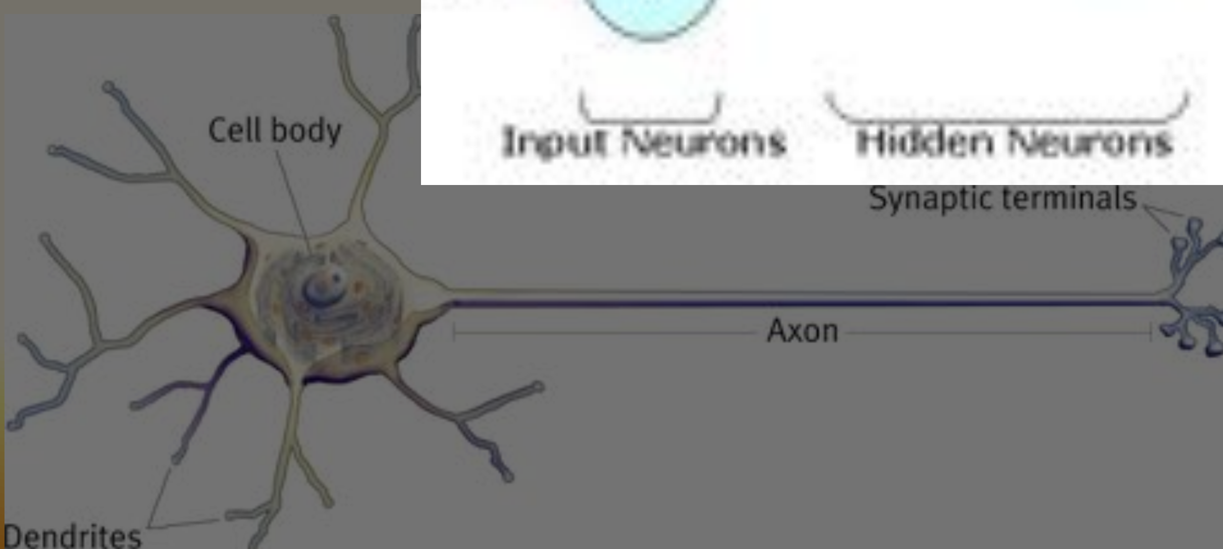
Marr: Implementation level

- Goal:
  - What is the physical implementation?
- What they do not answer:
  - Why is the implementation like this? What is the purpose (computational)
  - What is done? What strategies? (algorithmic)
- Common characteristics:
  - Describe WHERE in the brain the process occurs
  - WHAT areas are connected to each other and HOW
  - Many many minor details, small time scale

Example: Implementation level







Abstraction continuum

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More detailed

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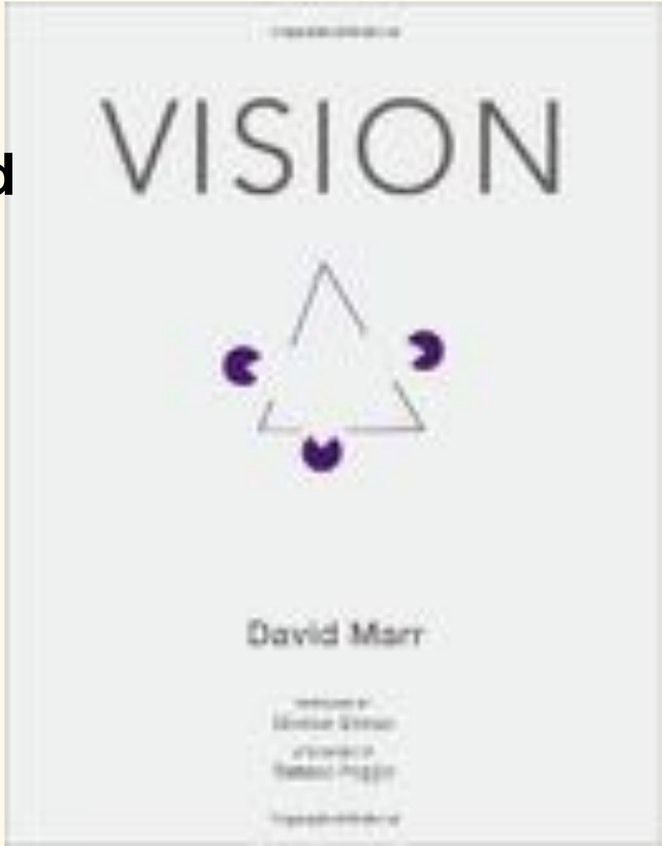

Example implementation level

- (Artificial) Neural networks:
  - E.g. Learning of past tense
    (e.g., Rummelhart & McClelland, 1986)
- Good neuroscience models

- Architecture oriented implementation models…
  - Chris Eliasmith (U. Waterloo)
    - http://arts.uwaterloo.ca/~celiasmi/
  - Randall O'Reilly (U. Colorado)
    - http://psych.colorado.edu/~oreilly/