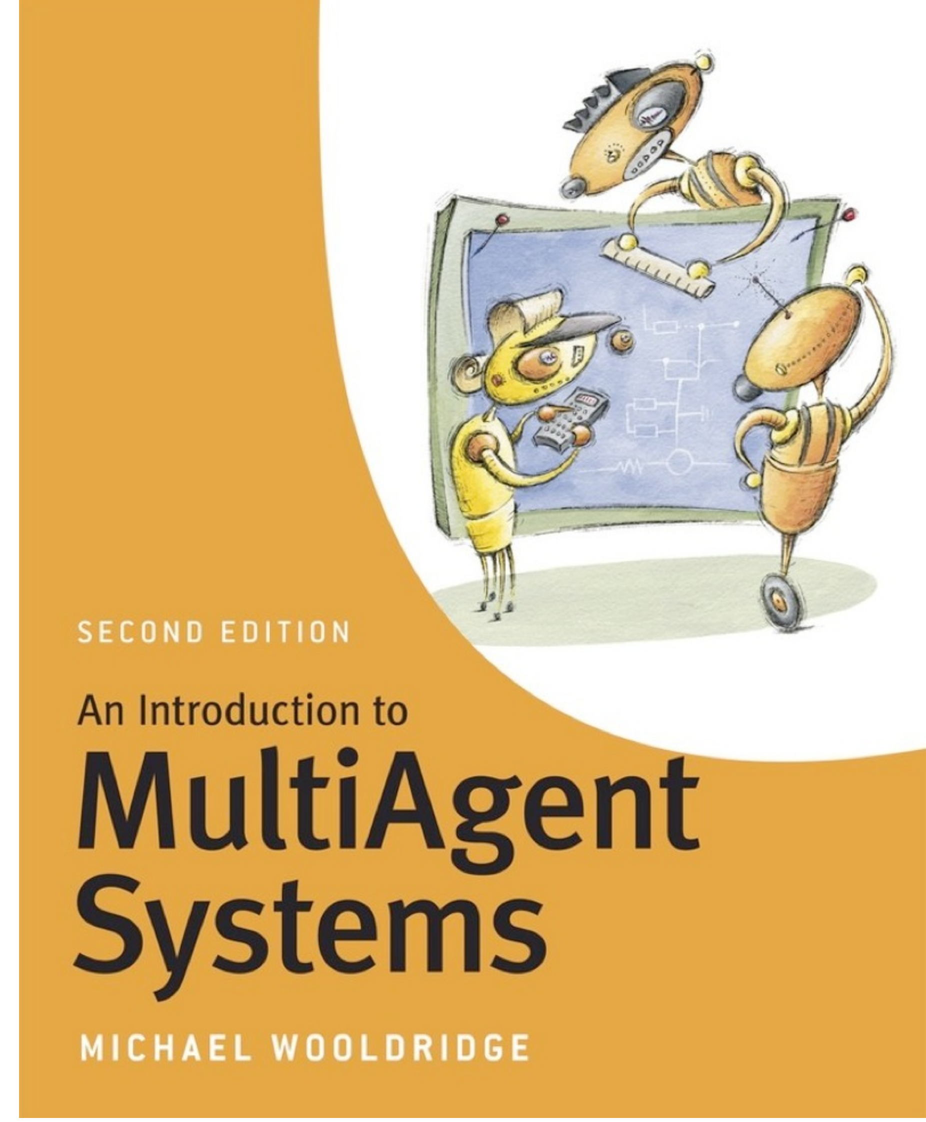


COMP310 MultiAgent Systems

Chapter 5 - Reactive and Hybrid Architectures

UNIVERSITY OF LIVERPOOL

Reactive Architectures

- There are many unsolved (some would say insoluble) problems associated with symbolic AI.
  - These problems have led some researchers to question the viability of the whole paradigm, and to the development of ***reactive*** architectures.
  - Although united by a belief that the assumptions underpinning mainstream AI are in some sense wrong, reactive agent researchers use many different techniques.

- In this presentation, we start by reviewing the work of one of the most vocal critics of mainstream AI: *Rodney Brooks*.

Brooks
Behavioural Languages

- Brooks proposed the following three theses:
  1. Intelligent behaviour can be generated ***without*** explicit ***representations*** of the kind that symbolic AI proposes.
  2. Intelligent behaviour can be generated ***without*** explicit ***abstract reasoning*** of the kind that symbolic AI proposes.
  3. Intelligence is an ***emergent*** property of certain complex systems.

Brooks Behavioural Languages

- He identified two key ideas that have informed his research:

  1. ***Situatedness and embodiment***: 'Real' intelligence is situated in the world, not in disembodied systems such as theorem provers or expert systems.
  2. ***Intelligence and emergence***: 'Intelligent' behaviour arises as a result of an agent's interaction with its environment. Also, intelligence is 'in the eye of the beholder'; it is not an innate, isolated property.

- To illustrate his ideas, Brooks built some agents based on his ***subsumption architecture***.

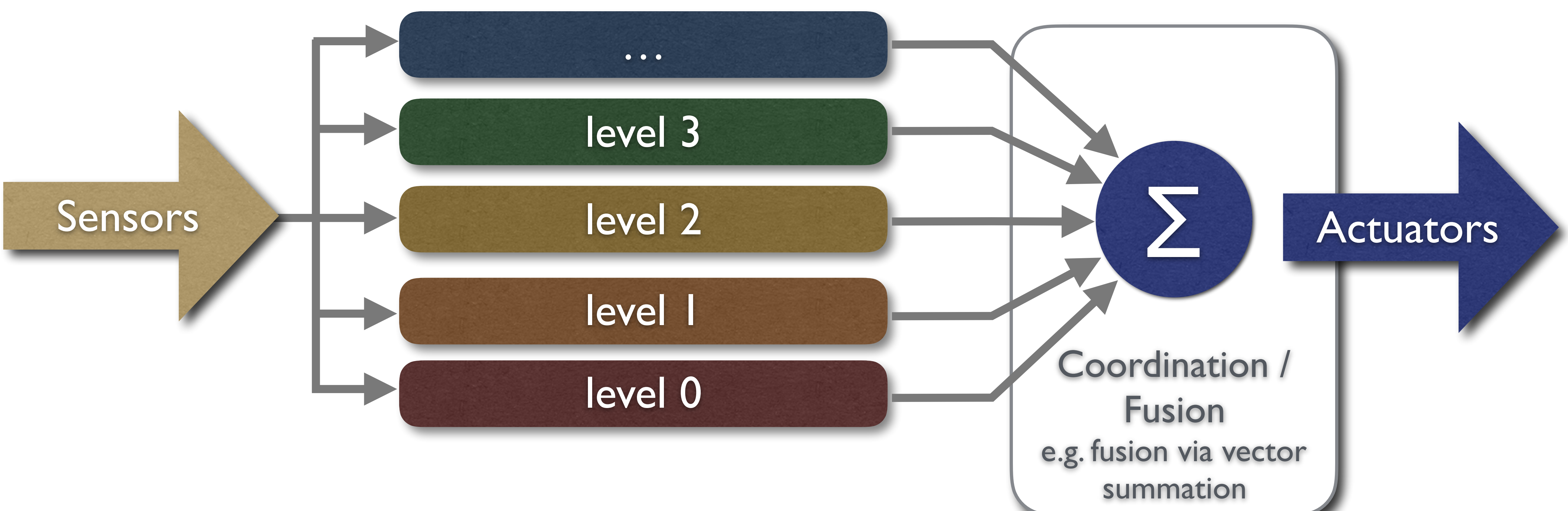
Subsumption Architecture

- A subsumption architecture is a hierarchy of task-accomplishing ***behaviours***.
  - Each behaviour is a rather simple rule-like structure.
  - Each behaviour 'competes' with others to exercise control over the agent.
  - Lower layers represent more primitive kinds of behaviour, (such as avoiding obstacles), and have precedence over layers further up the hierarchy.

- The resulting systems are, in terms of the amount of computation they do, ***extremely*** simple.
  - Some of the robots do tasks that would be impressive if they were accomplished by symbolic AI systems.

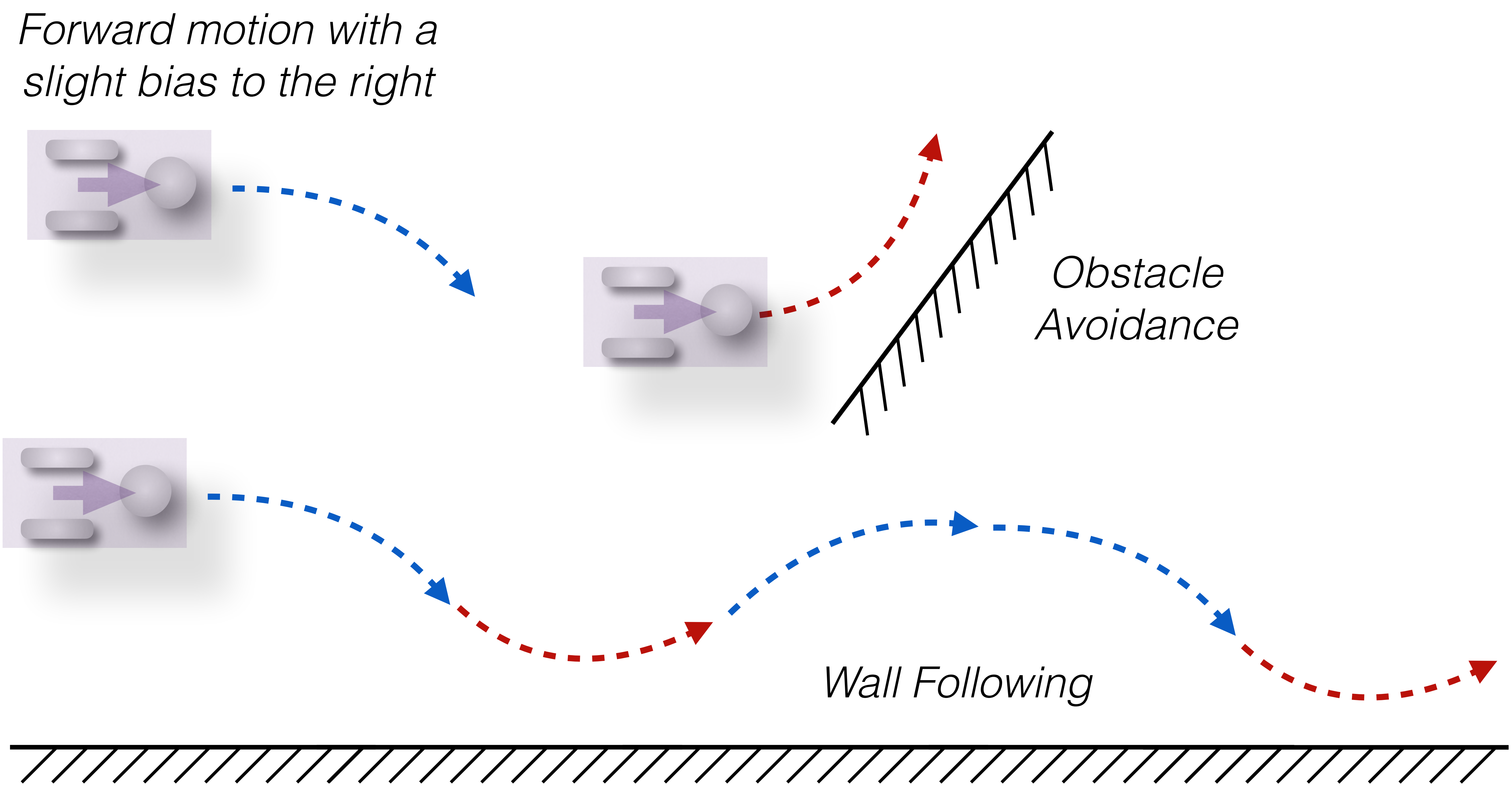
Subsumption Architecture

- It is the piling up of layers that gives the approach of its power.
- Complex behaviour emerges from simple components.
- Since each layer is independent, each can independently be:
    - Coded / Tested / Debugged
- Can then assemble them into a complete system.



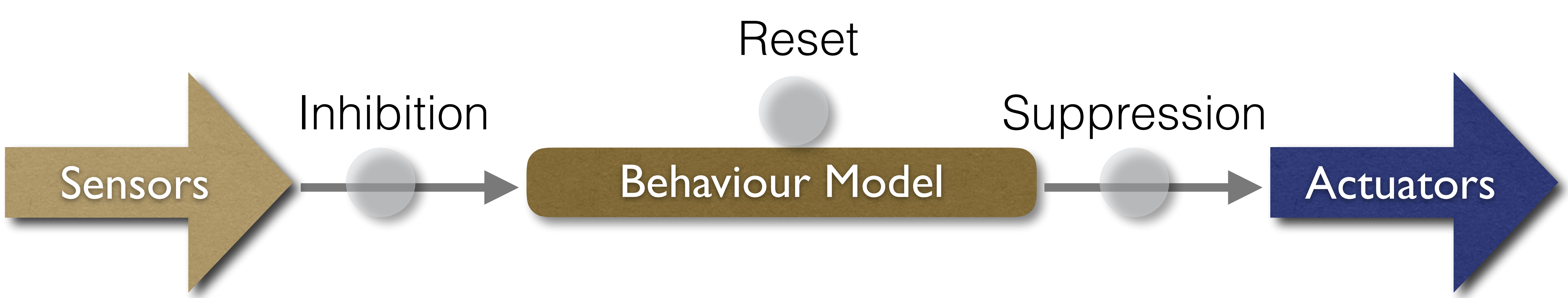
Emergent Behaviour

- Putting simple behaviours together leads to synergies



Abstract view of a Subsumption Machine

- Layered approach based on levels of competence
  - Higher level behaviours ***inhibit*** lower levels
- Augmented finite state machine:



Toto

- Maja Mataric´'s Toto is based on the subsumption architecture
  - Can map ***spaces*** and ***execute plans*** without the need for a ***symbolic*** representation.
  - Inspired by "…*the ability of insects such as bees to identify shortcuts between feeding sites*…"

- Each feature/landmark is a set of sensor readings
  - Signature
- Recorded in a behaviour as a triple:
  - Landmark type
  - Compass heading
  - Approximate length/size
- Distributed topological map.

Toto

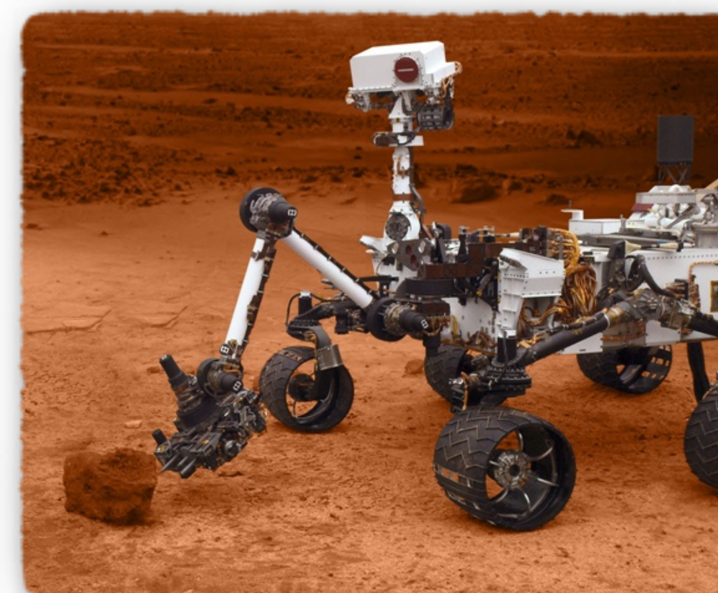
- Whenever Toto visited a particular landmark, its associated map behaviour would become activated
  - If no behaviour was activated, then the landmark was new, so a new behaviour was created
  - If an existing behaviour was activated, it inhibited all other behaviours
- Localization was based on which behaviour was active.
  - No map object, but the set of behaviours clearly included map functionality.

Steel’s Mars Explorer System

- Steels’ Mars explorer system, using the ***subsumption*** architecture, achieves near-optimal cooperative performance in simulated ‘rock gathering on Mars’ domain:

Objective

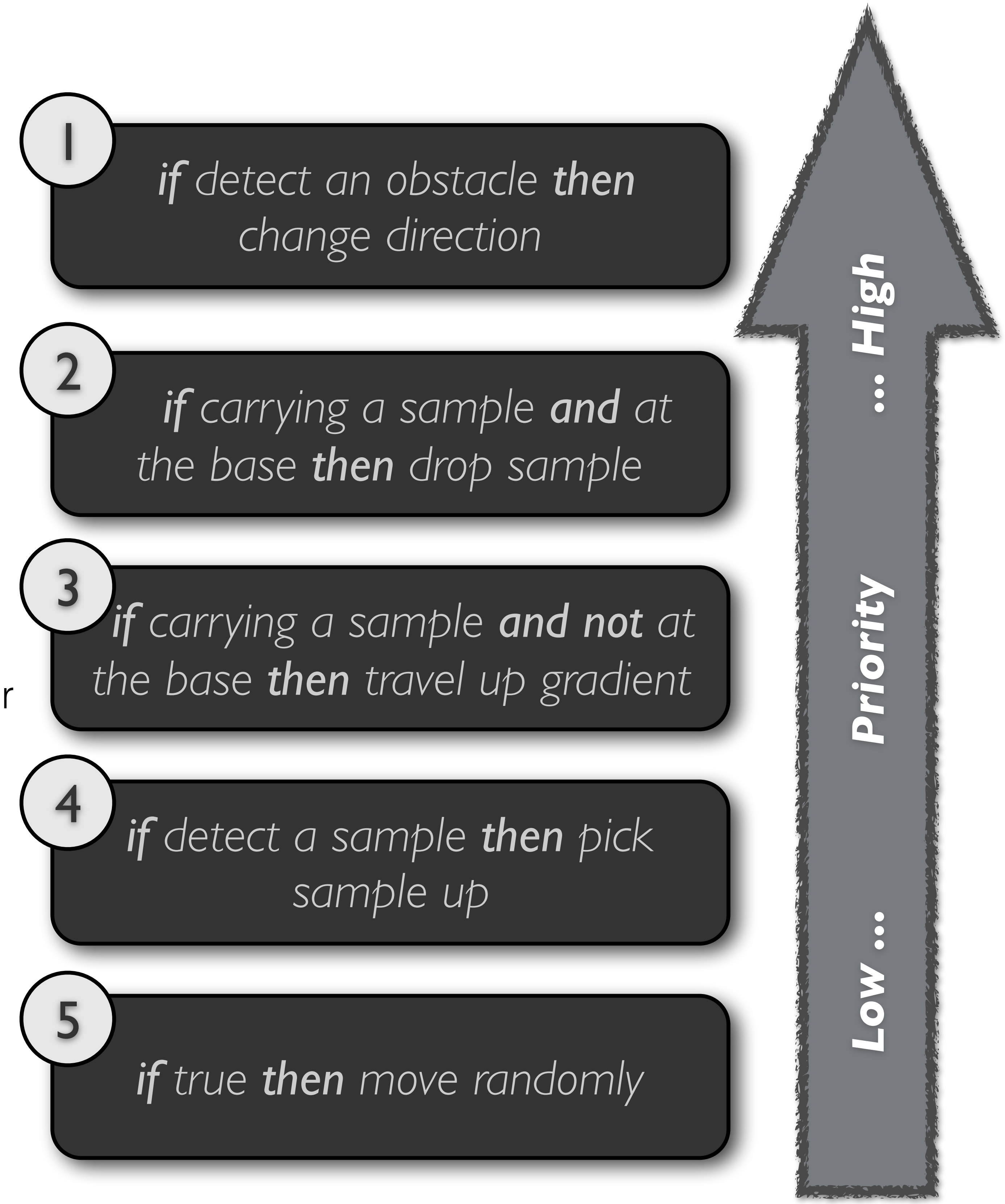
To explore a distant planet, and in particular, to collect sample of a precious rock. The location of the samples is not known in advance, but it is known that they tend to be clustered.



- ***Individual behaviour*** is governed by a set of simple rules.
- ***Coordination between agents*** can also be achieved by leaving “markers” in the environment.

Steel's Mars Explorer System

1. For individual (non-cooperative) agents, the lowest-level behavior, (and hence the behavior with the highest "priority") is obstacle avoidance.
2. Any samples carried by agents are dropped back at the mother-ship.
3. If not at the mother-ship, then navigate back there.
   - The "gradient" in this case refers to a virtual "hill" radio signal that slopes up to the mother ship/base.
4. Agents will collect samples they find.
5. An agent with "nothing better to do" will explore randomly. This is the highest-level behaviour (and hence lowest level "priority").



Steel's Mars Explorer System

- Existing strategy works well when samples are distributed randomly across the terrain.
  - However, samples are located in clusters
  - Agents should ***cooperate*** with each other to locate clusters
- Solution to this is based on foraging ants.
  - Agents leave a "radioactive" trail of crumbs when returning to the mother ship with samples.
    - If another agent senses this trail, it follows the trail back to the source of the samples
    - It also picks up some of the crumbs, making the trail fainter.
    - If there are still samples, the trail is reinforced by the agent returning to the mother ship (leaving more crumbs)
    - If no samples remain, the trail will soon be erased.

•
•

3' ***if*** *carrying samples* ***and not*** *at the base* ***then*** *drop 2 crumbs* ***and*** *travel up gradient.*

•
•
•

4.5 ***if*** *sense crumbs* ***then*** *pick up 1 crumb* ***and*** *travel down gradient*

•
•

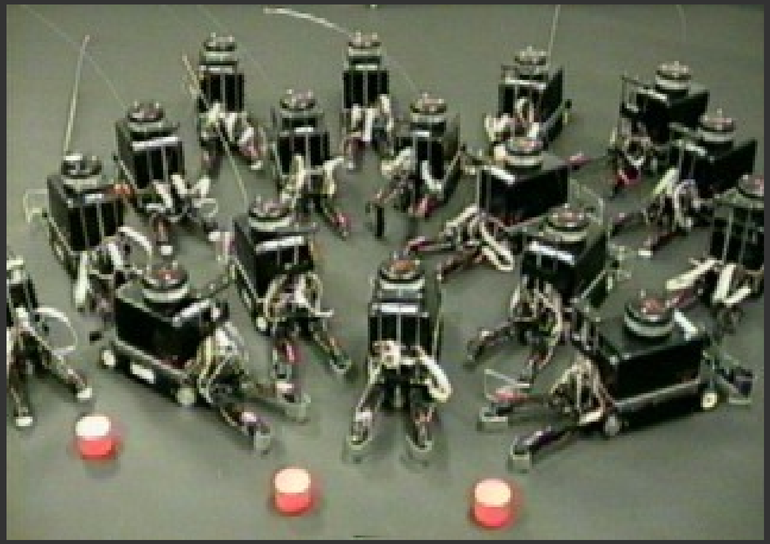
Emergent behaviour

- Important but not well-understood phenomenon
  - Often found in behaviour-based/reactive systems
- Agent behaviours "emerge" from interactions of rules with environment.
  - Sum is greater than the parts.
  - The interaction links rules in ways that weren't anticipated.

- ***Coded behaviour***: In the programming scheme
- ***Observed behaviour***: In the eyes of the observer
  - There is no one-to-one mapping between the two!
- When observed behaviour "exceeds" programmed behaviour, then we have emergence.

Emergent Flocking

Flocking is a classic example of emergence, e.g. Reynolds "Boids", or Mataric´'s "nerd herd".



Each agent uses the following three rules:

1. *Don't run into any other robot*
2. *Don't get too far from other robots*
3. *Keep moving if you can*

When run in parallel on many agents, the result is flocking

Situated Automata

- Approach proposed by Rosenschein and Kaelbling.
  - An agent is specified in a rule-like (declarative) language.
    - Then compiled down to a digital machine, which satisfies the declarative specification.
  - This digital machine can operate in a ***provable time bound***.
  - Reasoning is done ***off line***, at compile time, rather than ***online at run time***.

- The theoretical limitations of the approach are not well understood.
  - ***Compilation*** (with propositional specifications) is equivalent to an NP-complete problem.
  - The more expressive the agent specification language, the harder it is to compile it.

Situated Automata

- An agent is specified by perception and action
  - Two programs are used to synthesise agents:

1. RULER specifies the perception component

RULER takes as its input three components...

"…[A] specification of the semantics of the [agent's] inputs ("whenever bit 1 is on, it is raining"); a set of static facts ("whenever it is raining, the ground is wet"); and a specification of the state transitions of the world ("if the ground is wet, it stays wet until the sun comes out"). The programmer then specifies the desired semantics for the output ("if this bit is on, the ground is wet"), and the compiler … [synthesises] a circuit whose output will have the correct semantics… All that declarative "knowledge" has been reduced to a very simple circuit…"

Kaelbling, L.P. (1991) A Situated Automata Approach to the Design of Embedded Agents. SIGART Bulletin, 2(4): 85-88

2. GAPPS specifies the action component
   - Takes a set of goal reduction rules and a top-level goal (symbolically specified) and generates a non-symbolic program

Limitations of Reactive Systems

- Although there are clear advantages of Reactive Systems, there are also limitations!
  - If a model of the environment isn't used, then sufficient information of the local environment is needed for determining actions
  - As actions are based on local information, such agents inherently take a "short-term" view
  - Emergent behaviour is very hard to engineer or validate; typically a trial and error approach is ultimately adopted
  - Whilst agents with few layers are straightforward to build, models using many layers are inherently complex and difficult to understand.

Hybrid Architectures

- Many researchers have argued that neither a completely deliberative nor completely reactive approach is suitable for building agents.

- They have suggested using ***hybrid*** systems, which attempt to marry classical and alternative approaches.

- An obvious approach is to build an agent out of two (or more) subsystems:
  - a ***deliberative*** one, containing a symbolic world model, which develops plans and makes decisions in the way proposed by symbolic AI; and
  - a ***reactive*** one, which is capable of reacting to events without complex reasoning.

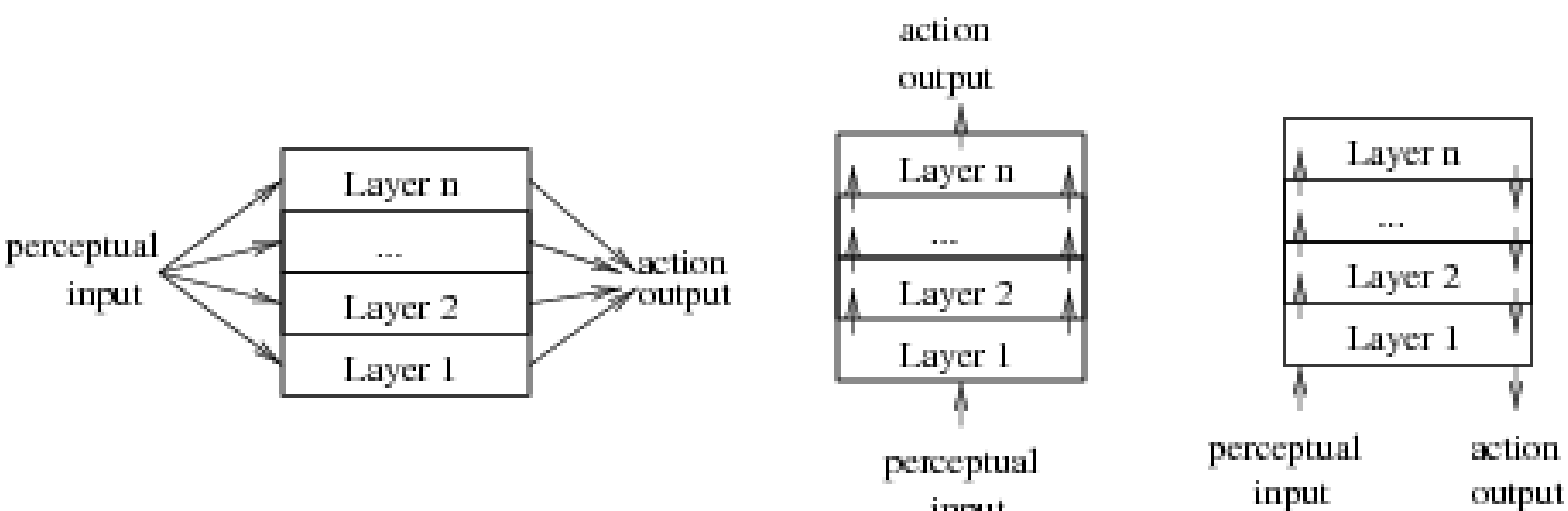
Hybrid Architectures

- Often, the reactive component is given some kind of precedence over the deliberative one.
- This kind of structuring leads naturally to the idea of a layered architecture, of which ***InterRap*** and ***TouringMachines*** are examples.
  - In such an architecture, an agent's control subsystems are arranged into a ***hierarchy***…
  - …with higher layers dealing with information at ***increasing levels of abstraction***.
- A key problem in such architectures is what kind control framework to embed the agent's subsystems in, to manage the interactions between the various layers.

Hybrid Architectures

- ***Horizontal layering.***
  - Layers are each directly connected to the sensory input and action output.
  - In effect, each layer itself acts like an agent, producing suggestions as to what action to perform.

- ***Vertical layering.***
  - Sensory input and action output are each dealt with by at most one layer each.



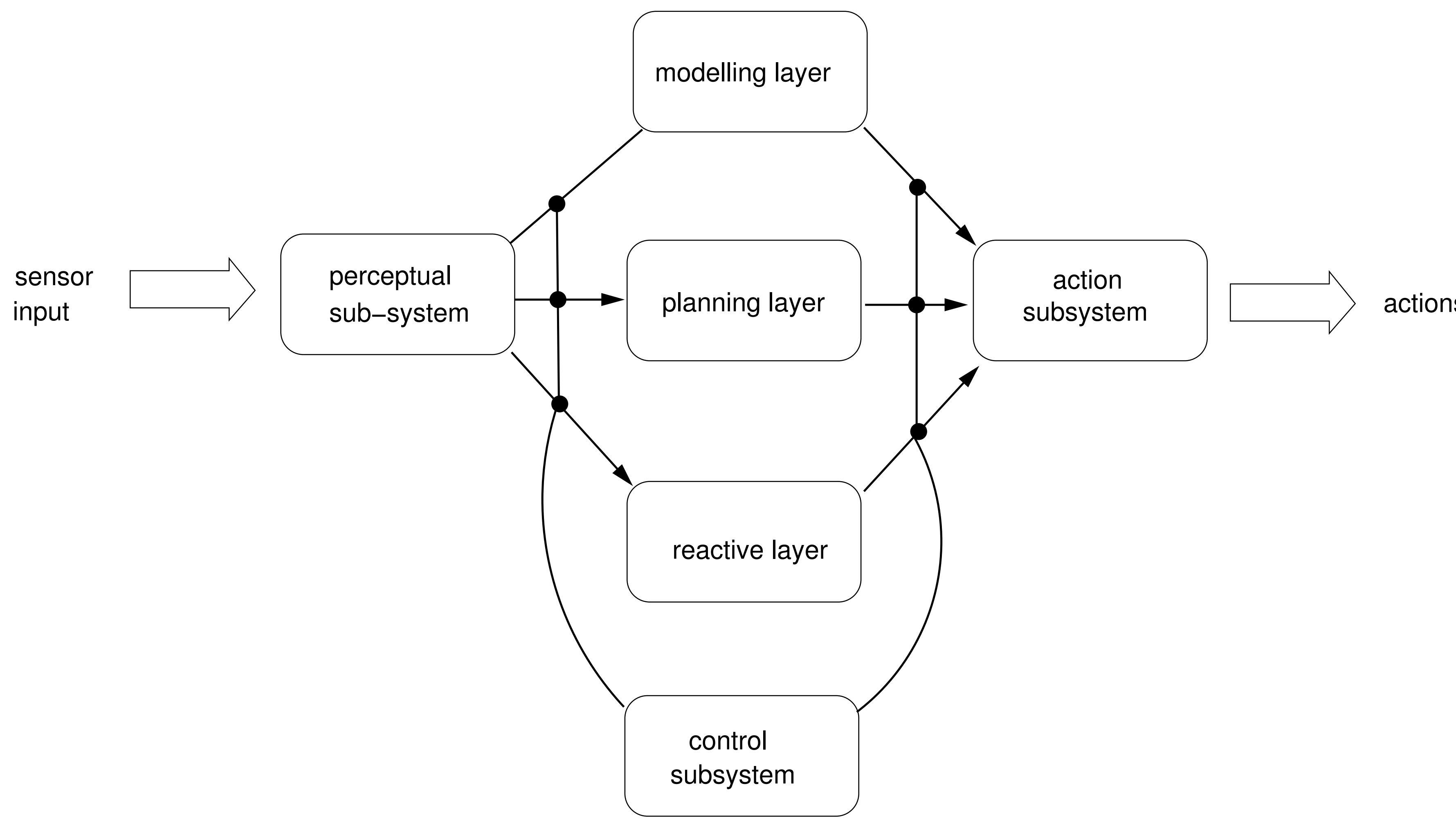
(a) Horizontal layering

(b) Vertical layering (One pass control)

(c) Vertical layering (Two pass control)

Ferguson - TouringMachines

- The TouringMachines architecture consists of perception and action subsystems
  - These interface directly with the agent's environment, and three control layers, embedded in a control framework, which mediates between the layers.



Ferguson - TouringMachines

- The ***reactive layer*** is implemented as a set of situation-action rules, a` la subsumption architecture.
- Example:

```
rule-1: kerb-avoidance
    if
        is-in-front(Kerb, Observer) and
        speed(Observer) > 0 and
        separation(Kerb, Observer) < KerbThreshHold
    then
        change-orientation(KerbAvoidanceAngle)
```

- The planning layer constructs plans and selects actions to execute in order to achieve the agent's goals.

Ferguson - TouringMachines

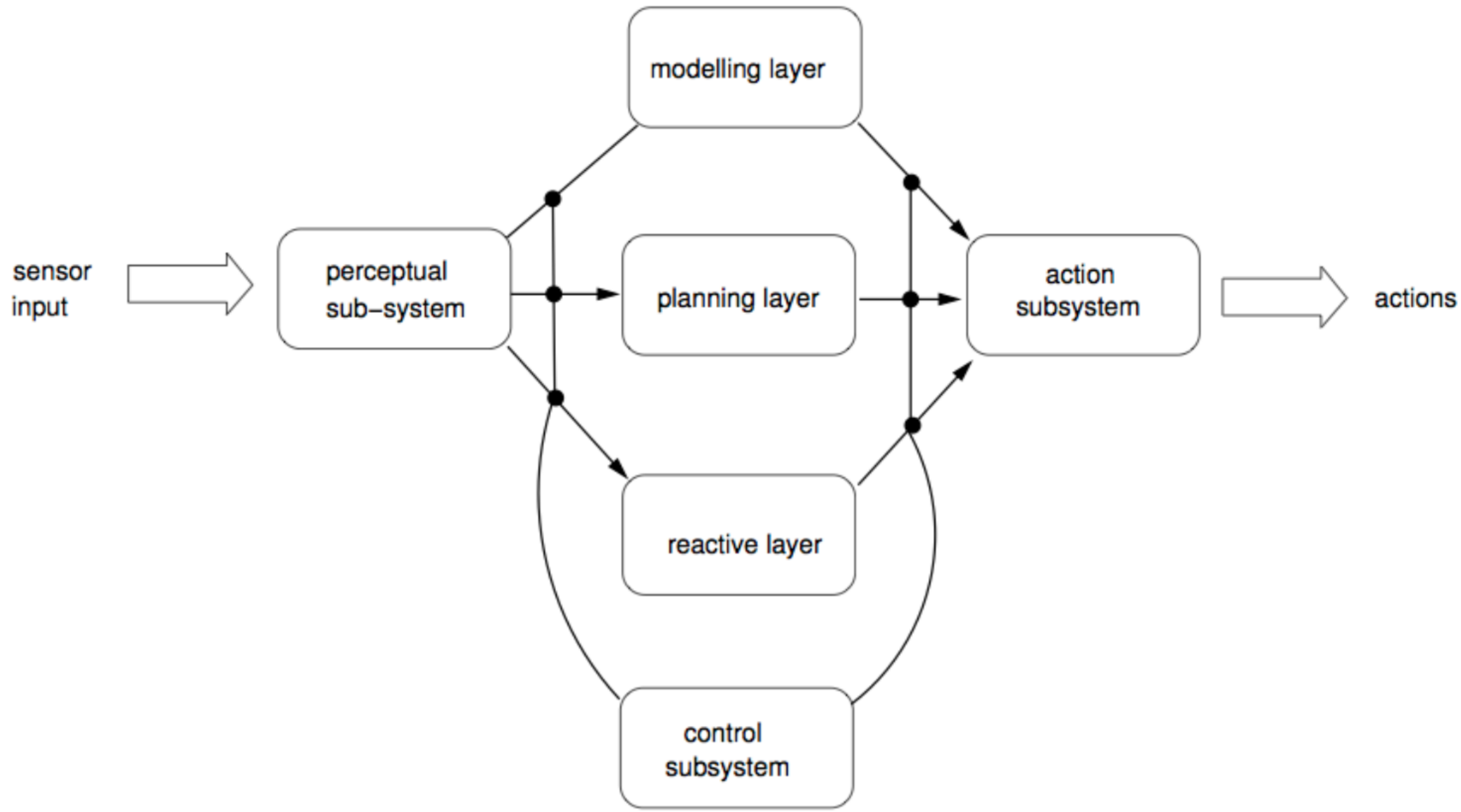
- The ***modelling layer*** contains symbolic representations of the ‘cognitive state’ of other entities in the agent’s environment.
- The three layers communicate with each other and are embedded in a control framework, which use control rules.
- Example:

```
censor-rule-1:
    if
        entity(obstacle-6) in perception-buffer
    then
        remove-sensory-record(layer-R, entity(obstacle-6))
```

- Such control structures have become common in robotics.

Question 2.a

2. (a) The following diagram illustrates the key subsystems of the TOURINGMACHINES agent architecture:



Describe the overall operation of the architecture, making sure you explain how the three decision layers achieve the goal of reactive, pro-active behaviour. **(15 marks)**

Q2.a answer

The Touring Machines architecture is an example of a hybrid architecture that combines reactive behaviour with that of deliberative, or pro-active behaviour. It consists of three layers, each of which operate in parallel. Each has access to the perceptual sub-system, which is responsible for converting the percepts obtained from sensor input into predicates that can be used for reasoning. In addition, each layer can result in the generation of actions that can then be executed. A control subsystem is responsible for monitoring the incoming percepts held in the perceptual sub-system, and then determining which of the actions (if any) should be executed from the different layers; i.e. it determines which layer is responsible for controlling the agent. In particular, the control subsystem can suppress sensor information going to certain layers, or it can censor actions generated by the different layers.

The reactive layer is responsible for responding to changes in the environment (in a similar way to Bookes subsumption architecture). A set of situation-action rules are defined, which then fire if they map to sensor input. For example, if the agent is controlling an autonomous vehicle and it detects a kerb unexpectedly in front of the vehicle, it can stop (or slow down) and turn to avoid the kerb.

The planning layer is responsible for determining the actions necessary to achieve the agent's goals. Under normal operation, this layer determines what the agent should do. This is done by making use of a set of planning schema, relating to different goals, and then performing the necessary actions. Note that no low level planning is performed.

The modelling layer represents the various entities in the world. This is responsible for modelling the world, including other agents, and for determining the agents goals, or planning goals that resolve any conflicts with other agents if such conflicts are detected. Whenever a goal is generated, it is passed onto the planning layer, which then determines the final actions.

Although several of the details here are from your notes, much more description was originally given in the lecture, and is also available from the course text book.

Stanley

- Won the 2005 DARPA Grand Challenge
  - Consists of 30 different independently operating modules across 6 layers

The key challenge...
was not one of action,
but one of perception...

Global Services Layer

User Interface Layer

Vehicle Interface Layer

Planning and Control layer

Perception layer

Sensor interface layer

Summary

- This lecture has looked at two further kinds of agent:
  - Reactive agents; and
  - Hybrid agents.
- Reactive agents build complex behaviour from simple components.
- Hybrid agents try to combine the speed of reactive agents with the power of deliberative agents.

Class Reading (Chapter 5):

"A Robust Layered Control System for a Mobile Robot,", Rodney A. Brooks. IEEE Journal of Robotics and Automation, 2(1), March 1986, pp. 14–23. (*also MIT AI Memo 864, September 1985*)

A provocative, fascinating article, packed with ideas. It is interesting to compare this with some of Brook's later - arguably more controversial - articles