ROBOTICS WITH PLYMOUTH UNIVERSITY

ROCO318
Mobile and Humanoid Robots
Part 7 – Robot Control

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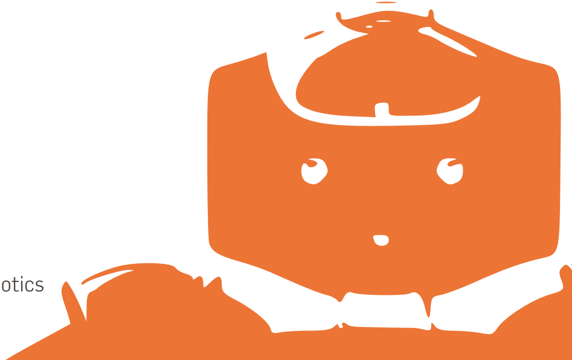
Plymouth University



How hard might it be?

LET'S THINKER A LITTLE...

Let's imagine you want to build a robot that **fetches beers from the fridge** and bring them back to you whenever you ask. It should **not kill the cat**, and it should **politely greet your mum** whenever it sees her.

You have:

- a map with the important landmarks like `fridge`
- the following modules:

`speech_synthesis` `open_fridge`

`pick_up_beer` `detect_cat`

`follow_path_to`

`plan_to` `detect_mum`

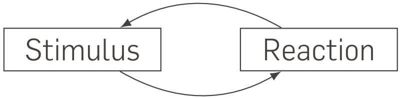
`process_verbal_commands`

Can you draw a control architecture that achieves just that?

CONTROL PARADIGMS

BEHAVIOURAL (OR REACTIVE) CONTROL

Behaviours are small programs that read sensors and control actuators. Each behaviour does **one simple thing**; it typically has access to all sensors/actuators.



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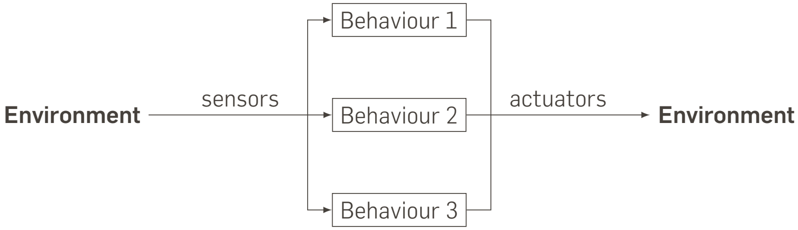
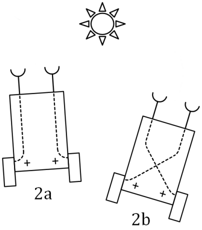


We only want one behaviour at a time! Need to **prioritise**: behaviours can *override* or **subsume** less important ones.

EXTREME CASE: BRAITENBERG MACHINES

- Motion directly controlled by sensors (typically photocells)
- Yet the resulting behaviour may appear complex or even intelligent
- Can you guess the behaviours of vehicles 2a and 2b?



Source: Wikipedia

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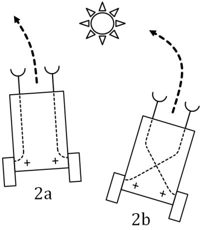

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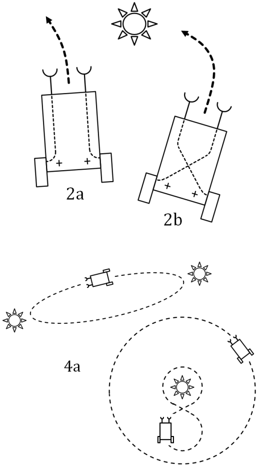


- Complex behaviours emerge (typically with non-linear control functions).

Source: Wikipedia

COMBINING BEHAVIOURS: EXAMPLE

Three behaviours:

- **Follow a robot**

  Sensor: IR communication
  Behaviour: follow another robot

- **Avoid obstacle**

  Sensors: bumpers
  Behaviour: move away from the wall

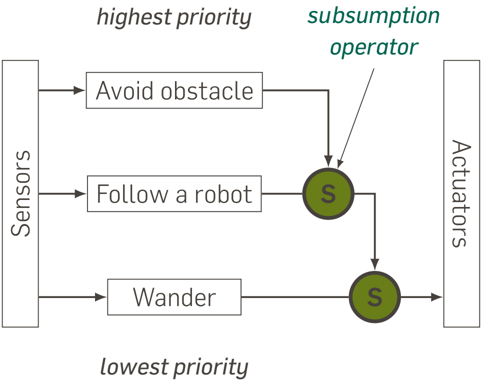
- **Wander**

  Sensors: encoders
  Behaviour: move forward and turn

Which behaviour should have the highest priority? the lowest?

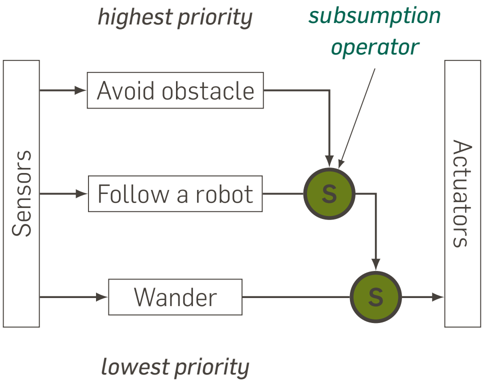
Source: example borrowed from Rice University ENGI128

COMBINING BEHAVIOURS: EXAMPLE



We combine behaviours by **subsuming** lower-priority behaviours whenever a higher-priority behaviour becomes active.

COMBINING BEHAVIOURS: EXAMPLE



We combine behaviours by **subsuming** lower-priority behaviours whenever a higher-priority behaviour becomes active.

→ **subsumption architecture**

BEHAVIOURAL CONTROL: STRENGTHS/WEAKNESSES

Strengths

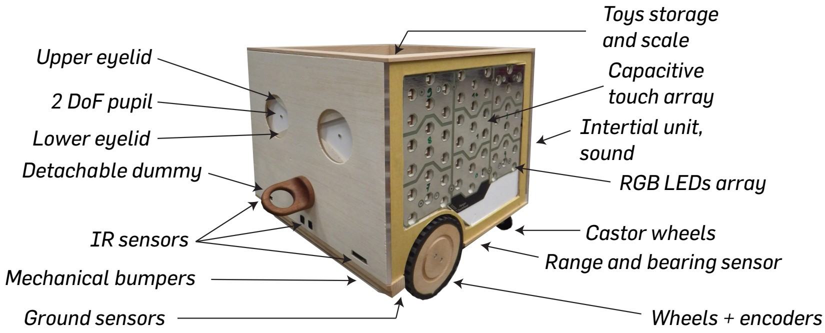
- **Incremental development**
- By definition **modular**
- Effective to react to events → well suited to **dynamic environments**

Weaknesses

- **goal-oriented behaviours hard to implement** (“what will my robot do?”)
- **importance of the arbiter**: who inhibits (i.e. *subsumes*) who might be context-dependent
- debugging difficult (need to trace which behaviours are active)

EVENT-ORIENTED PROGRAMMING: EXAMPLE OF RANGER

Ranger is a 'box on wheels' developed at EPFL



EVENT-ORIENTED PROGRAMMING

Event-oriented programming is a possible way of implementing a behavioural control paradigm:

```
with Ranger() as robot:

    robot.background_blink()
    robot.look_at_touches()

    robot.whenever("dummy", becomes = True)
                                .do(on_dummy)
    robot.whenever("dummy", becomes = False)
                                .do(on_dummy_removed)
    robot.whenever("scale", increase = 0.3).do(on_toy)
    robot.whenever("bumper", becomes = True).do(on_bumper)

    while True:
        time.sleep(0.1)
```

EVENT-ORIENTED PROGRAMMING

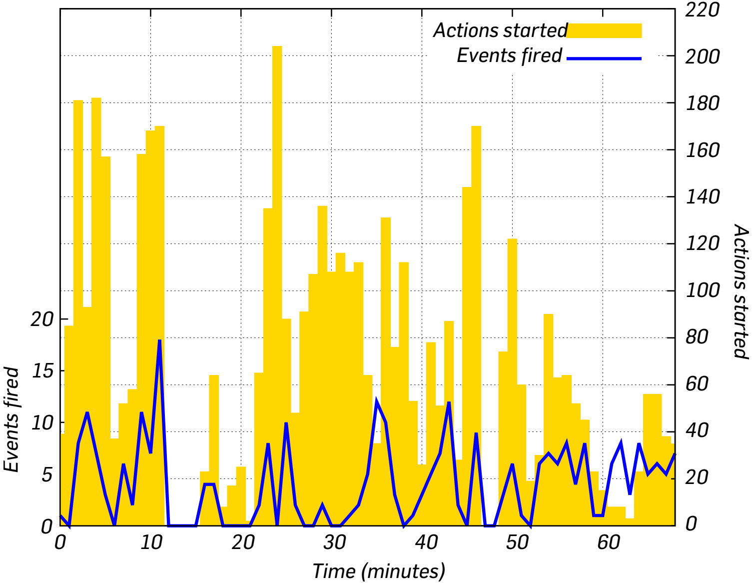
Event-oriented programming is a possible way of implementing a behavioural control paradigm:

```
def on_dummy(robot):
    robot.look_at_dummy()
    robot.blink()
    sleep = robot.fall_asleep()
    robot.lightbar(RAINBOW).wait()
    sleep.wait()

def on_dummy_removed(robot):
    robot.light_bar(colors.rand())
    robot.wakeup().wait()
    robot.move(0.4, v = 0.8).wait()
    robot.idle().wait()
```

```
def on_bumper(robot):
    pulse = robot.pulse_row(0)
    while abs(robot.state.v) > 0.01:
        robot.sleep(0.2)
    pulse.cancel()

def on_toy(robot):
    robot.playsound(SOUNDS["toy_in"])
    robot.lightbar(RAINBOW).wait()
```

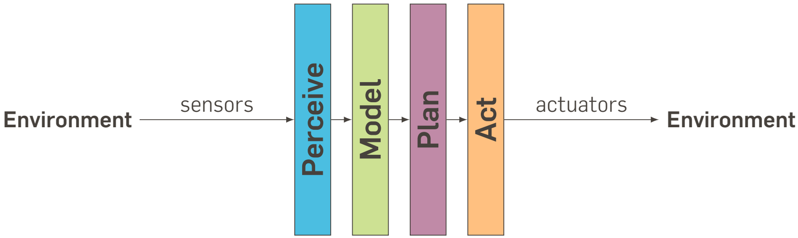


Actions started
Events fired
Events fired
Actions started
Time (minutes)
0
10
20
30
40
50
60
0
5
10
15
20
0
20
40
60
80
100
120
140
160
180
200
220

Note that this is a example of **aimless, purely reactive**, behaviour.

MODEL-PLAN-ACT

Basic paradigm for **deliberative architectures**.



TASK PLANNING

Turn a high-level goal (*bring me a beer!*) into 'simple' **primitive** actions.

A standard approach relies on **Hierarchical task networks** (**HTN**): uses partial-order contraints to *decompose actions* into *primitive operators*.

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$\boxed{\text{Bring me a beer!}}$

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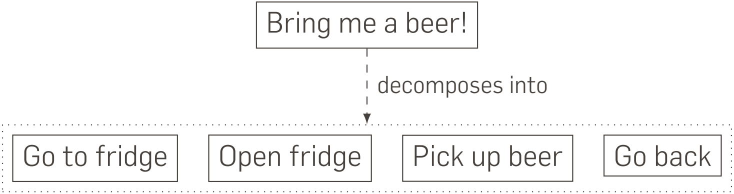

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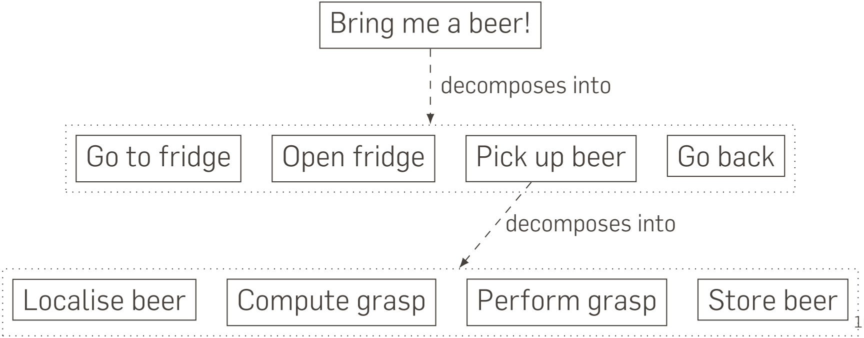


TASK PLANNING

What ***primitive action*** means is system-dependent: what an agent considers as primitive can be another agent's plans.

TASK PLANNING: ACTIONS

An action has **pre-conditions** and **post-conditions** (or *effects*).

```
Action <action name>
{
    preconditions {...};
    effects{...};
    cost{<cost_function_name>};
    duration{<duration_function_name>};
}
```

TASK PLANNING: ACTIONS

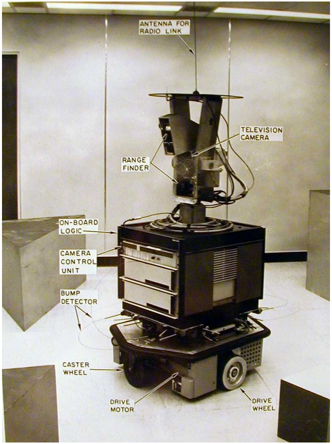
An action has **pre-conditions** and **post-conditions** (or *effects*).

```
Action <action name>
{
    preconditions {...};
    effects{...};
    cost{<cost_function_name>};
    duration{<duration_function_name>};
}

Action open_fridge
{
    preconditions {facing_fridge AND fridge_door.closed};
    effects {facing_fridge AND fridge_door.open};
}
```

EXAMPLE: SHAKEY THE ROBOT

Shakey the robot (Stanford, 1968), using the **STRIPS** planner



Go ...

Go to object bx
GOTOB(bx)
Preconditions: TYPE(bx,OBJECT),(∃rx)[INROOM(bx,rx) ∧ INROOM(ROBOT,rx)]
Deletions: AT(ROBOT,$1,$2), NEXTTO(ROBOT,$1)
Additions: *NEXTTO(ROBOT,bx)

Go to door dx.
GOTOD(dx)
Preconditions: TYPE(dx,DOOR),(∃rx)(∃ry)[INROOM(ROBOT,rx) ∧ CONNECTS(dx,rx,ry)]
Deletions: AT(ROBOT,$1,$2), NEXTTO(ROBOT,$1)
Additions: *NEXTTO(ROBOT,dx)

Go to coordinate location (x,y).
GOTOL(x,y)
Preconditions: (∃rx)[INROOM(ROBOT,rx) ∧ LOCINROOM(x,y,rx)]
Deletions: AT(ROBOT,$1,$2), NEXTTO(ROBOT,$1)
Additions: *AT(ROBOT,x,y)

Go through door dx into room rx.
GOTHRUDR(dx,rx)
Preconditions: TYPE(dx,DOOR), STATUS(dx,OPEN), TYPE(rx,ROOM), NEXTTO(ROBOT,dx) (∃ry)[INROOM(ROBOT,ry) ∧ CONNECTS(dx,ry,rx)]
Deletions: AT(ROBOT,$1,$2), NEXTTO(ROBOT$1), INROOM(ROBOT,$1)
Additions: *INROOM(ROBOT,rx)

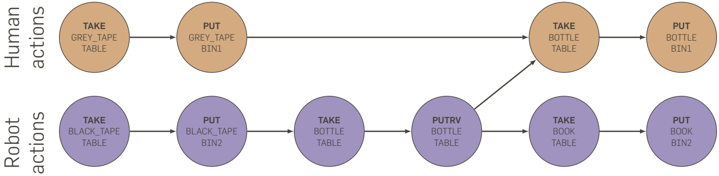

LAAS-CNRS

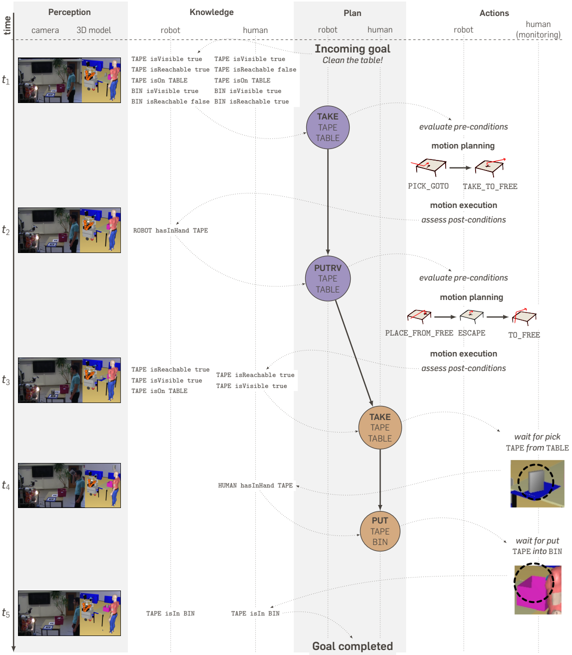
TASK PLANNING

Robot actions

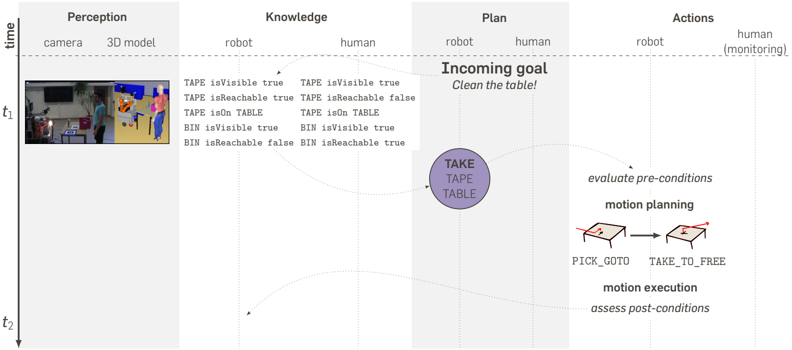
TAKE BLACK_TAPE TABLE → **PUT** BLACK_TAPE BIN2 → **TAKE** BOTTLE TABLE → **PUTRV** BOTTLE TABLE → **TAKE** BOOK TABLE → **PUT** BOOK BIN2

TASK PLANNING





time
Perception
camera
3D model
Knowledge
robot
human
Plan
robot
human
Actions
robot
human (monitoring)
Incoming goal
Clean the table!
t_1
TAPE isVisible true
TAPE isReachable true
TAPE isOn TABLE
BIN isVisible true
BIN isReachable false
TAPE isVisible true
TAPE isReachable false
TAPE isOn TABLE
BIN isVisible true
BIN isReachable true
TAKE TAPE TABLE
evaluate pre-conditions
motion planning
PICK_GOTO
TAKE_TO_FREE
motion execution
assess post-conditions
t_2
ROBOT hasInHand TAPE
PUTRV TAPE TABLE
evaluate pre-conditions
motion planning
PLACE_FROM_FREE
ESCAPE
TO_FREE
motion execution
assess post-conditions
t_3
TAPE isReachable true
TAPE isVisible true
TAPE isOn TABLE
TAPE isReachable true
TAPE isVisible true
TAKE TAPE TABLE
wait for pick
TAPE from TABLE
t_4
HUMAN hasInHand TAPE
PUT TAPE BIN
wait for put
TAPE into BIN
t_5
TAPE isIn BIN
TAPE isIn BIN
Goal completed


time
Perception
camera
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human
Plan
robot
human
Actions
robot
human (monitoring)
t_1
t_2
Incoming goal
Clean the table!
TAPE isVisible true
TAPE isReachable true
TAPE isOn TABLE
BIN isVisible true
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TAPE isOn TABLE
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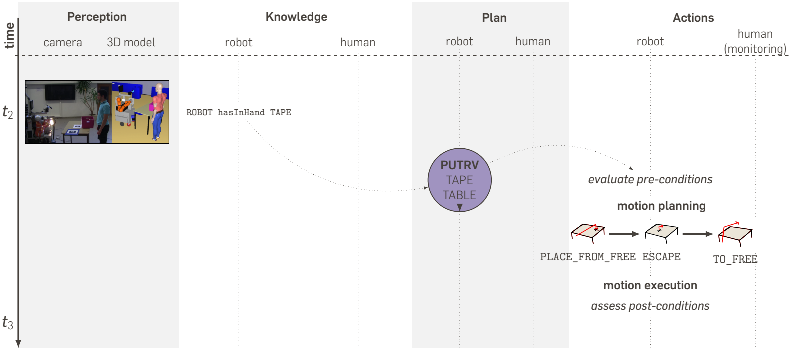
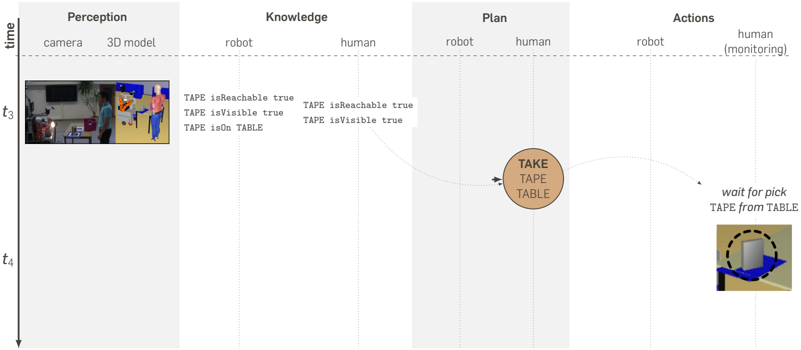
BIN isReachable true
TAKE TAPE TABLE
evaluate pre-conditions
motion planning
PICK_GOTO
TAKE_TO_FREE
motion execution
assess post-conditions



time
Perception
camera
3D model
Knowledge
robot
human
Plan
robot
human
Actions
robot
human (monitoring)
t2
ROBOT hasInHand TAPE
PUTRV
TAPE
TABLE
evaluate pre-conditions
motion planning
PLACE_FROM_FREE
ESCAPE
TO_FREE
motion execution
assess post-conditions
t3



Perception
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TAKE
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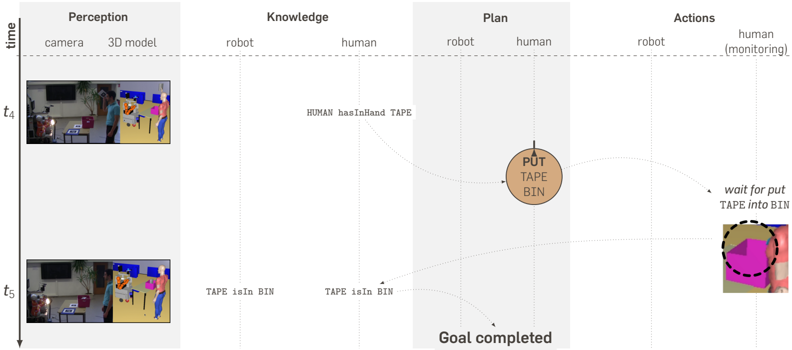
wait for pick
TAPE from TABLE



time
Perception
camera
3D model
Knowledge
robot
human
Plan
robot
human
Actions
robot
human
(monitoring)
t4
HUMAN hasInHand TAPE
PUT
TAPE
BIN
wait for put
TAPE into BIN
t5
TAPE isIn BIN
TAPE isIn BIN
Goal completed

MODEL/PLAN/ACT: STRENGTHS/WEAKNESSES

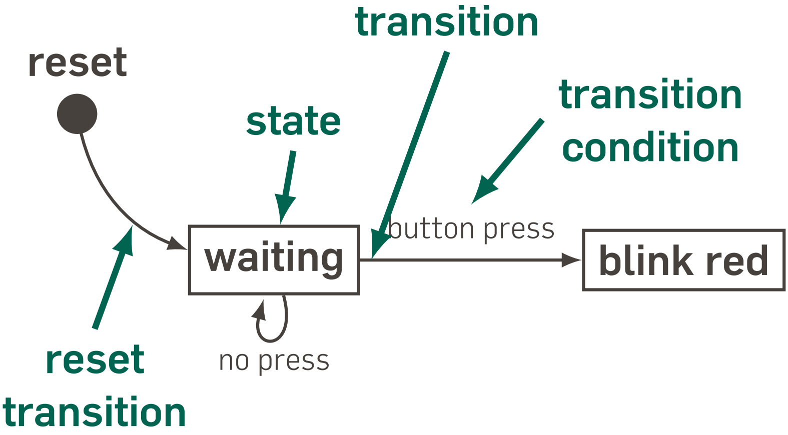
Strengths

- High-level goals are explicit
- Scale well with task complexity
- Easy to switch from one task to the other (planning domain is symbolic and explicit)

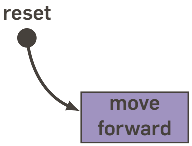
Weaknesses

- Modeling and planning might be (very) computationally expensive
- Difficult to deal with unexpected events: not well suited for dynamic environments (often requires replanning)

FINITE STATE MACHINES



FINITE STATE MACHINE: WALL AVOIDANCE EXAMPLE



Source: example borrowed from Rice University ENGI128

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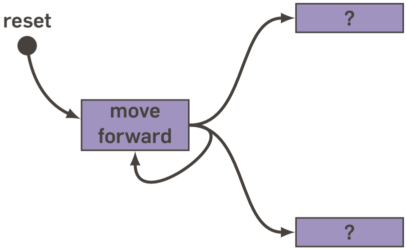

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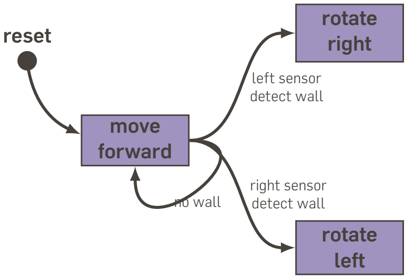

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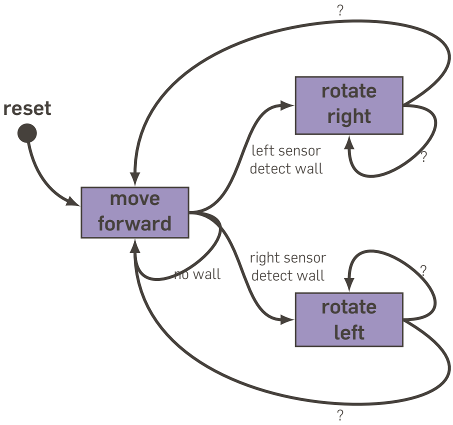

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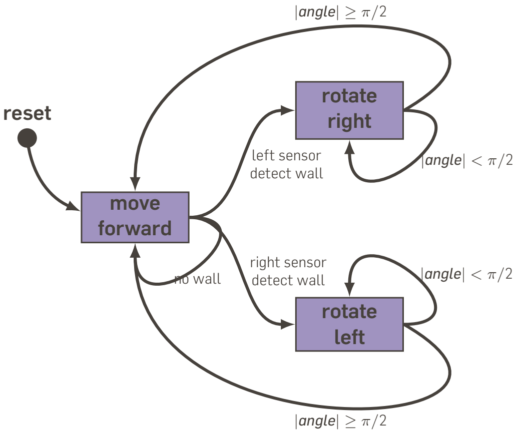
FINITE STATE MACHINE: WALL AVOIDANCE EXAMPLE



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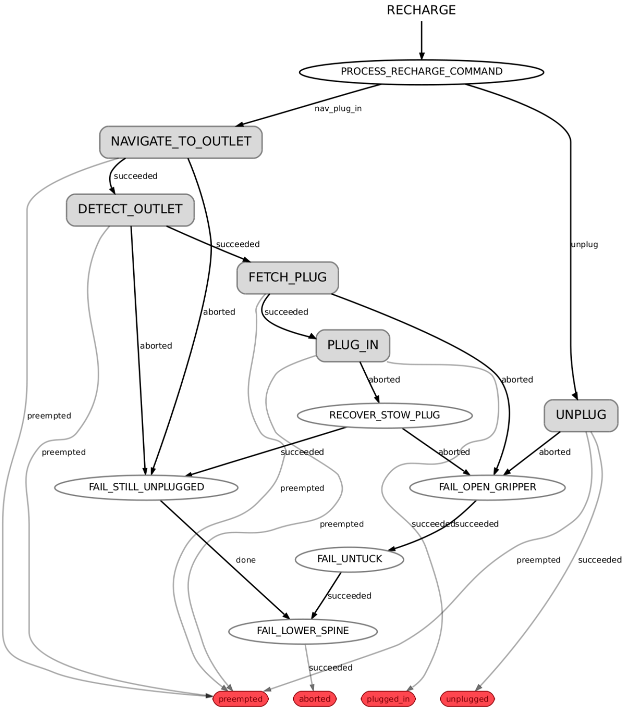
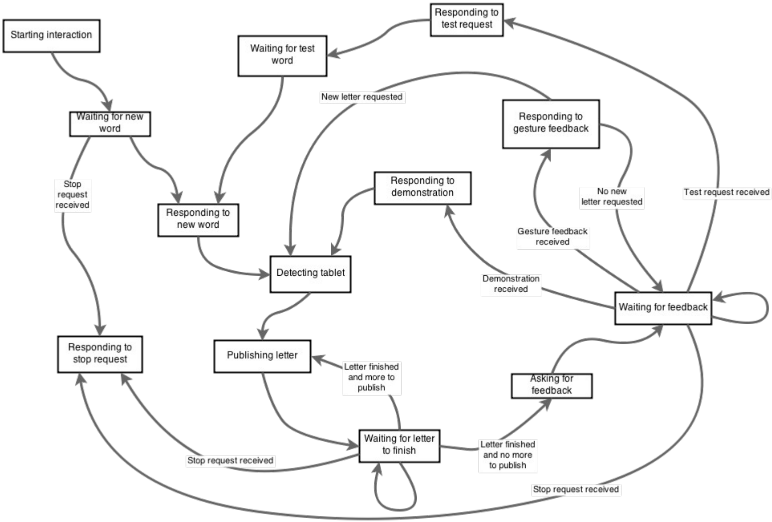


RECHARGE
PROCESS_RECHARGE_COMMAND
nav_plug_in
unplug
NAVIGATE_TO_OUTLET
succeeded
DETECT_OUTLET
succeeded
FETCH_PLUG
aborted
aborted
succeeded
PLUG_IN
aborted
aborted
RECOVER_STOW_PLUG
UNPLUG
preempted
preempted
succeeded
aborted
aborted
FAIL_STILL_UNPLUGGED
FAIL_OPEN_GRIPPER
preempted
preempted
succeededsucceeded
done
FAIL_UNTUCK
preempted
succeeded
succeeded
FAIL_LOWER_SPINE
succeeded
preempted
aborted
plugged_in
unplugged

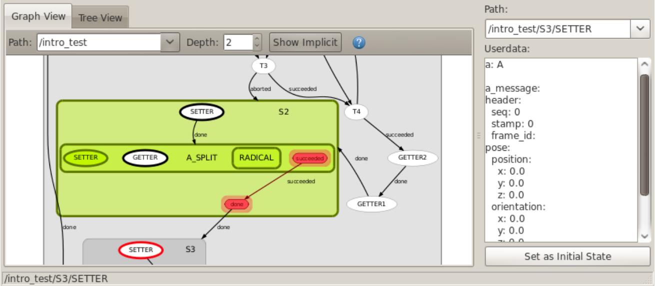


Starting interaction
Waiting for test word
Responding to test request
Waiting for new word
New letter requested
Responding to gesture feedback
Stop request received
Responding to new word
Responding to demonstration
No new letter requested
Test request received
Gesture feedback received
Detecting tablet
Demonstration received
Waiting for feedback
Responding to stop request
Publishing letter
Letter finished and more to publish
Asking for feedback
Waiting for letter to finish
Letter finished and no more to publish
Stop request received
Stop request received

FSM WITH ROS: THE SMACH PACKAGE

SMACH is a ROS-independent (but very weill integrated with ROS!) Python library to build state machines

- support for hierarchical (i.e. nested) state machines
- provides support for concurrency as well



RELATION TO BEHAVIOURAL/DELIBERATIVE PARADIGMS

Finite State Machines are **not a control paradigm** per-se.

Instead, they are a mathematical formalism to describe states and transitions.

States themselves might be behavioural components, deliberative components, or **nested state machines**.

FINITE STATE MACHINE: STRENGTHS/WEAKNESSES

Strengths

- Behaviour formally provable
- Easier to debug: control flow is explicit

Weaknesses

- Less modular than behavioural approaches
- Difficult to deal with unexpected events: not well suited for dynamic environments

CONTROL ARCHITECTURES

CONTROL STRATEGIES SO FAR

Behavioural or reactive

- *bottom-up* approach
- lots of independent modules executing concurrently, monitoring sensor values, triggering actions and possibly inhibiting each-others
- hard to organize into complex behaviours; gets messy quickly

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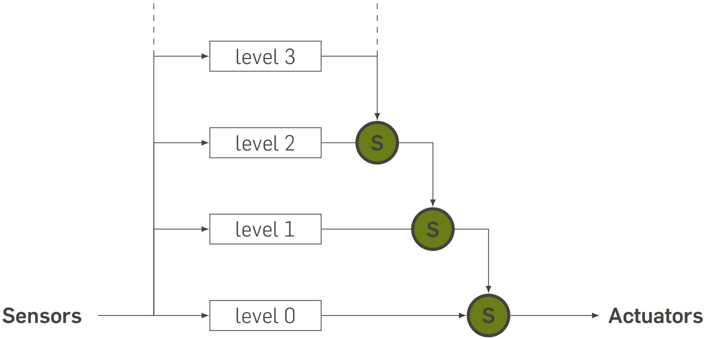
Behavioural or reactive

- *bottom-up* approach
- lots of independent modules executing concurrently, monitoring sensor values, triggering actions and possibly inhibiting each-others
- hard to organize into complex behaviours; gets messy quickly

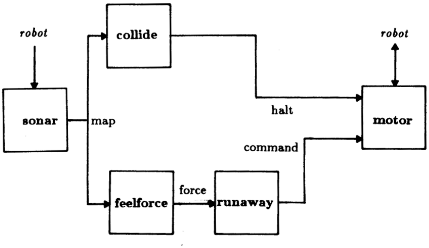
Hierarchical: classic model/plan/act

- *top-down* approach
- starts with high-level goals, decompose into sub-tasks
- not very agile

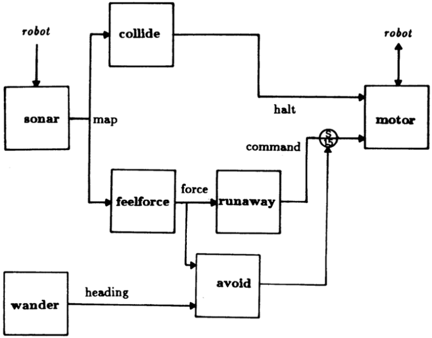
SUBSUMPTION ARCHITECTURE



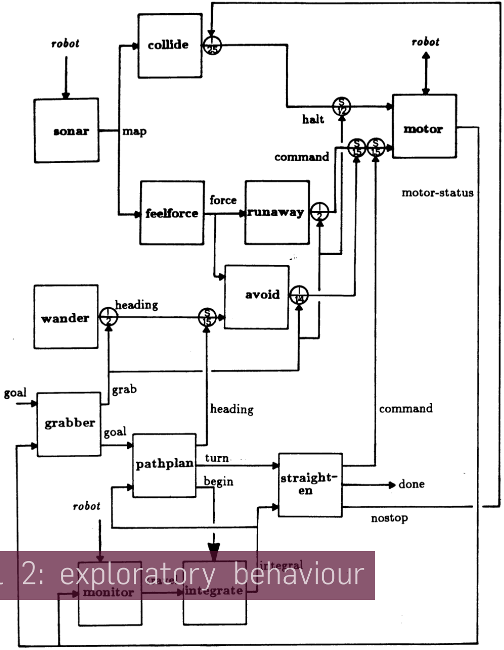
Source: Brooks, A robust layered control system for a mobile robot, 1986



Level 0: obstacle avoidance



Level 1: wander around aimlessly



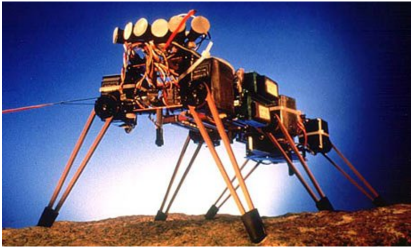
Level 2: exploratory behaviour

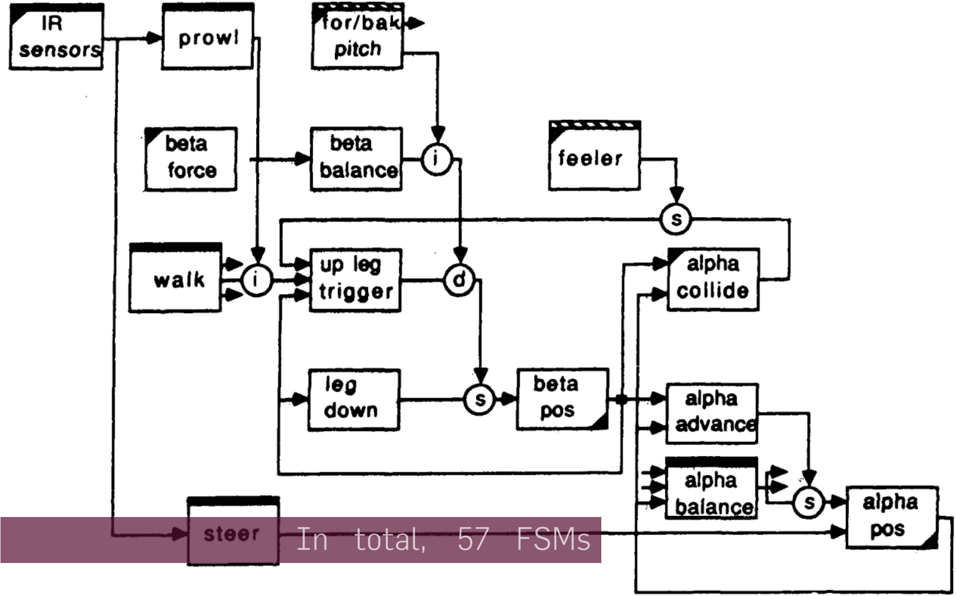
EXAMPLE: THE MIT GENGHIS ROBOT

MIT Genghis: Rodney Brooks in 1989

Really simple hardware

- 6 legs, 2 motors per leg
  - motor for forward/back,
  - motor for up/down
- 2 bump sensors (feelers)
- 2 ground detection sensors (switches)
- 6 heat sensors (but they weren't used for walking)





In total, 57 FSMs

CONTROL STRATEGIES SO FAR

Behavioural or reactive

- *bottom-up* approach
- lots of independent modules executing concurrently, monitoring sensor values, triggering actions and possibly inhibiting each-others
- hard to organize into complex behaviours; gets messy quickly

Hierarchical: classic model/plan/act

- *top-down* approach
- starts with high-level goals, decompose into sub-tasks
- not very agile

Hybrid approaches?

- Deliberative at high level, reactive at low level

LEVELS OF CONTROL

Control problems are usually split into three levels:

- **Low-level control**

  Example: where to place a leg as robot takes its next step
  Generally, continuous-valued problems
  Short time scale (under a second); high frequency loop

Source: CMU lecture on Cognitive Robotics

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- **High level control**

  What is the plan for moving these boxes out of the room?
  Discrete problems, long time scale (minutes)

Source: CMU lecture on Cognitive Robotics

LAYERED ARCHITECTURES

High-level layer
Deliberative/decisional layer

↓

Intermediate layer
Executive layer

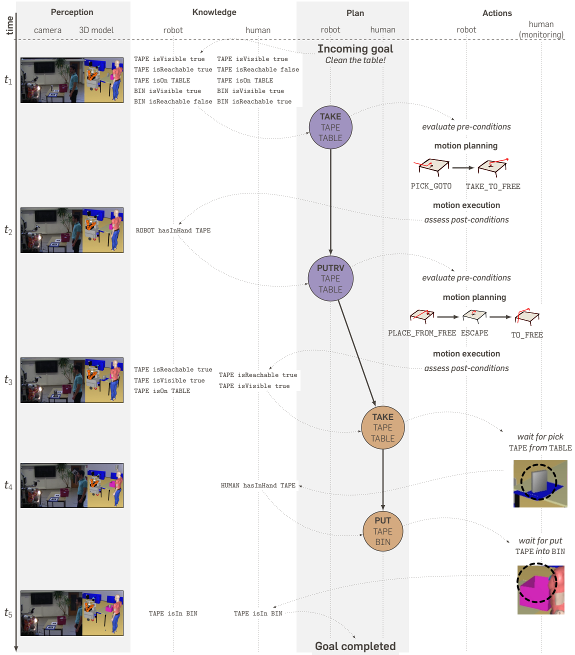
↓

Low-level layer
Functional layer

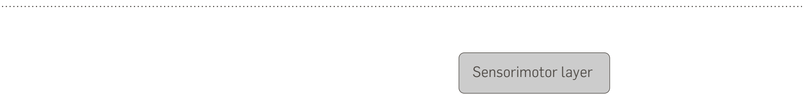
Each layer has different time constraints (from real-time to possibly ‘slow’); they typically use different control paradigms

DELIBERATIVE ARCHITECTURE FOR INTERACTION

One example: the LAAS deliberative architecture for interaction


time
Perception
camera
3D model
Knowledge
robot
human
Plan
robot
human
Actions
robot
human (monitoring)
Incoming goal
Clean the table!
t1
TAPE isVisible true
TAPE isReachable true
TAPE isOn TABLE
BIN isVisible true
BIN isReachable false
TAPE isVisible true
TAPE isReachable false
TAPE isOn TABLE
BIN isVisible true
BIN isReachable true
TAKE TAPE TABLE
evaluate pre-conditions
motion planning
PICK_GOTO
TAKE_TO_FREE
motion execution
assess post-conditions
t2
ROBOT hasInHand TAPE
PUTRV TAPE TABLE
evaluate pre-conditions
motion planning
PLACE_FROM_FREE
ESCAPE
TO_FREE
motion execution
assess post-conditions
t3
TAPE isReachable true
TAPE isVisible true
TAPE isOn TABLE
TAPE isReachable true
TAPE isVisible true
TAKE TAPE TABLE
wait for pick
TAPE from TABLE
t4
HUMAN hasInHand TAPE
PUT TAPE BIN
wait for put
TAPE into BIN
t5
TAPE isIn BIN
TAPE isIn BIN
Goal completed

DELIBERATIVE ARCHITECTURE FOR INTERACTION



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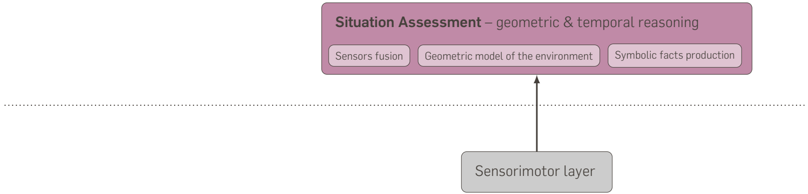

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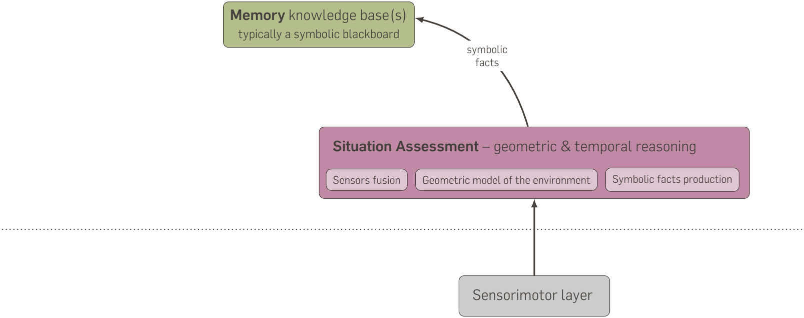

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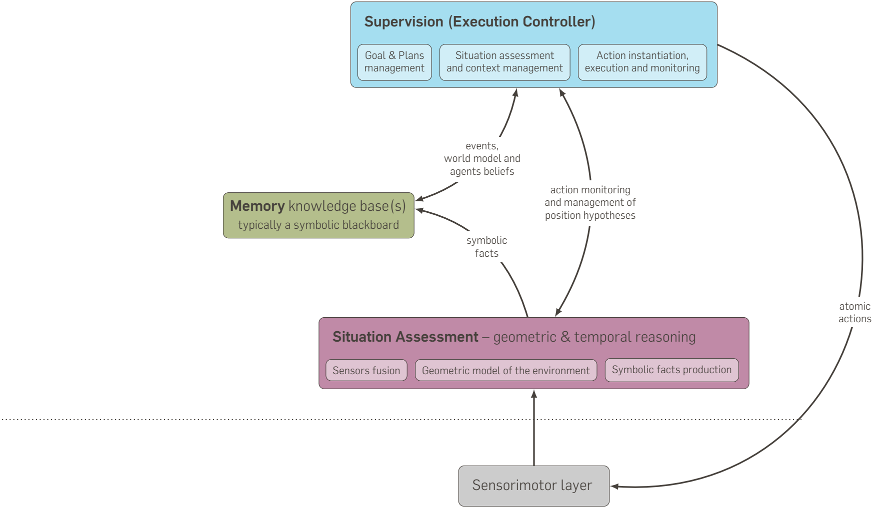

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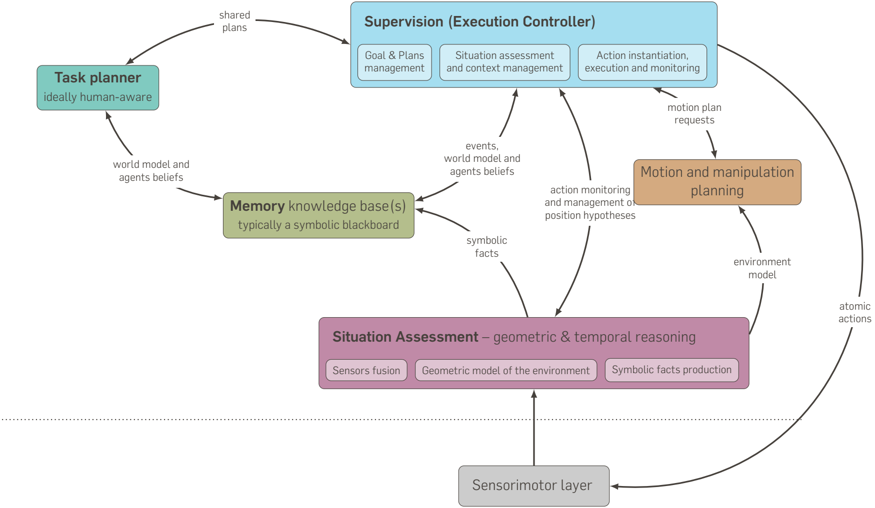

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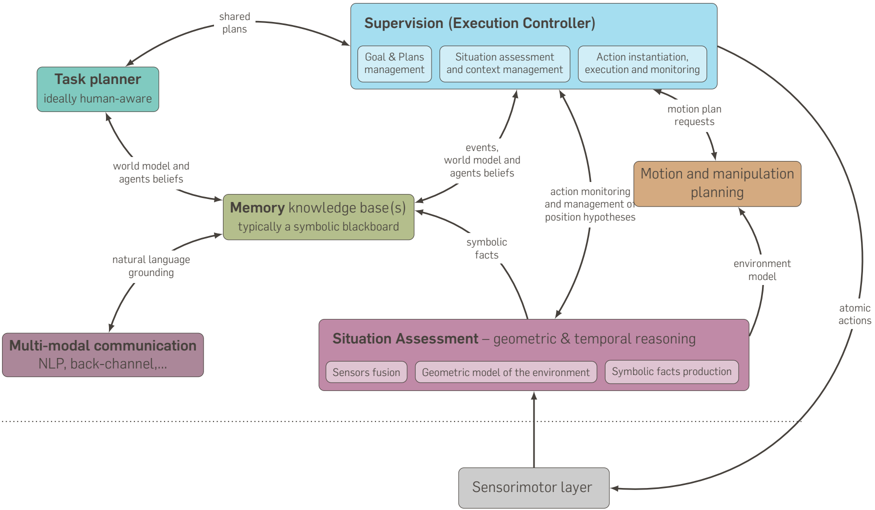
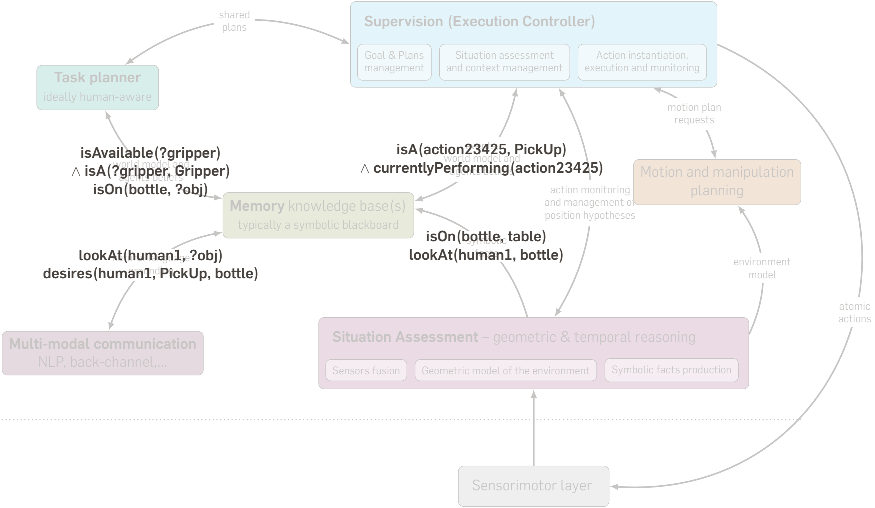


How do modules actually communicate with each other?

DELIBERATIVE ARCHITECTURE FOR INTERACTION



MIDDLEWARES

ROBOTIC MIDDLEWARES

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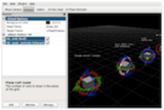
- It help with debugging (by providing **introspection** mechanisms)

MIDDLEWARES IN A BROADER SENSE

Plumbing

+



Tools

+

Capabilities

+

Ecosystem

EXISTING MIDDLEWARES

- OROCOS (Europe)
- YARP (Europe)
- OpenRTM (Korea)
- ROS – Robot Operating System (originally US)
- OpenRAVE (US)

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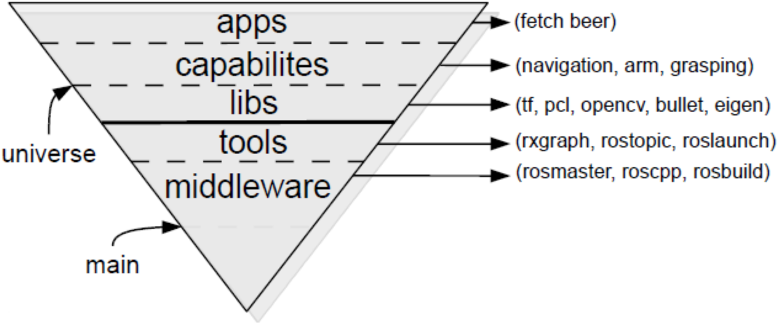
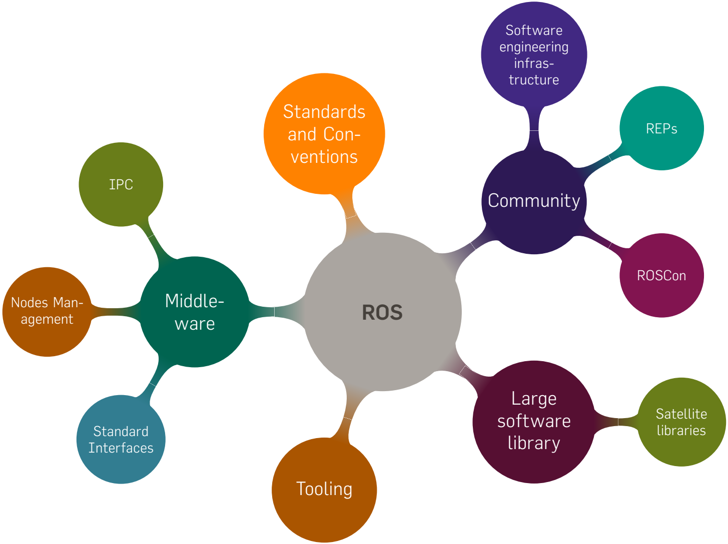
- A set of tools to run and monitor the nodes
- Engagement of a large academic community, leading to a library of thousands of nodes

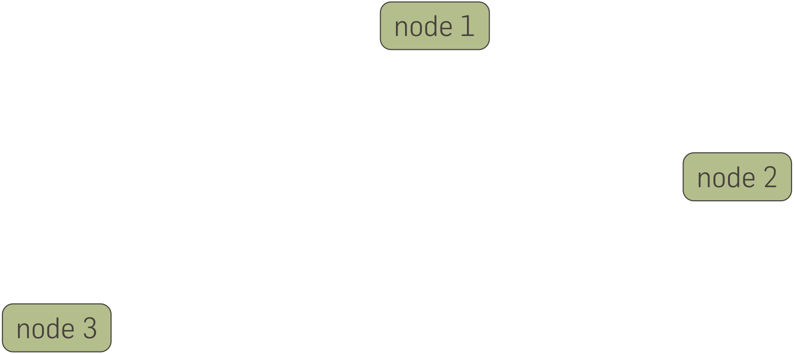
ROS STRUCTURE



ROS ECOSYSTEM



MIDDLEWARES' CORE PRINCIPLE: TALKING NODES



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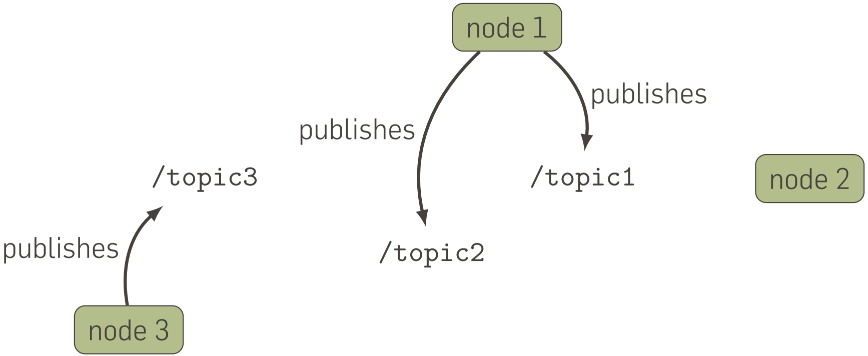

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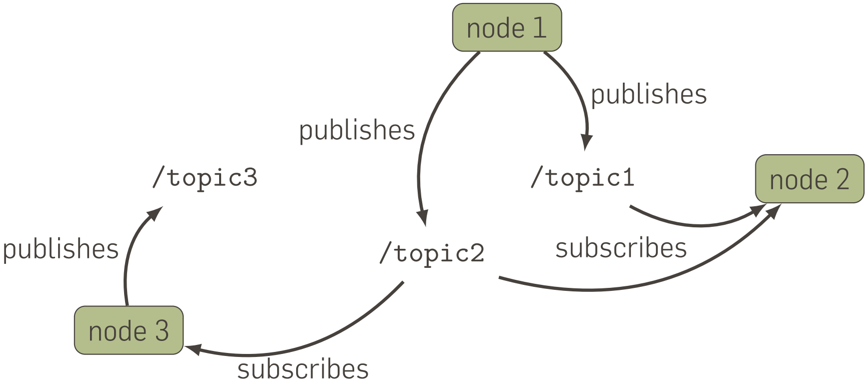

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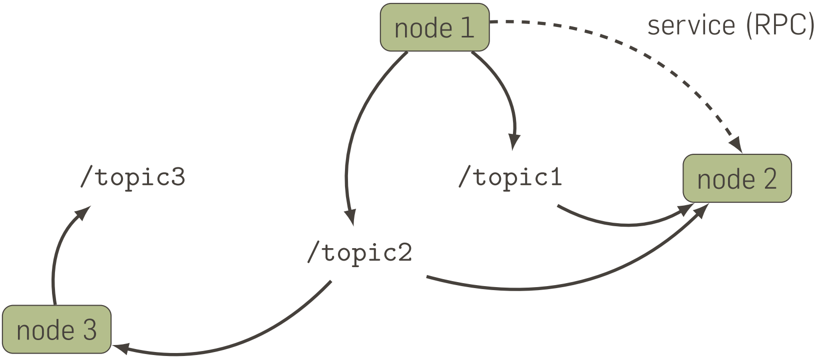

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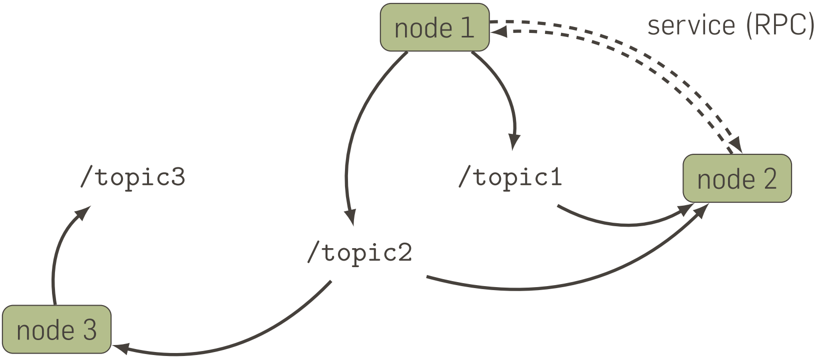

Services: **synchronous**

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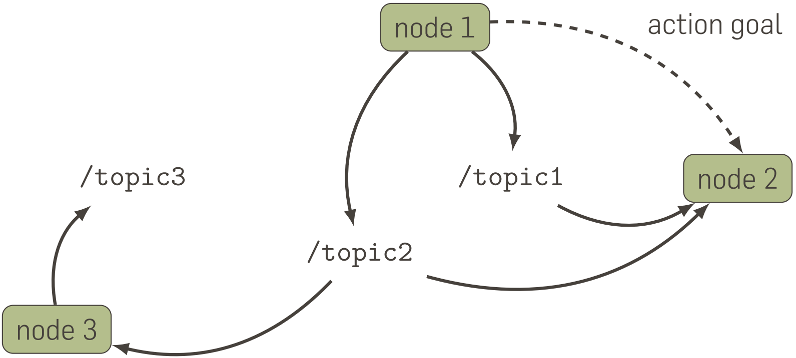

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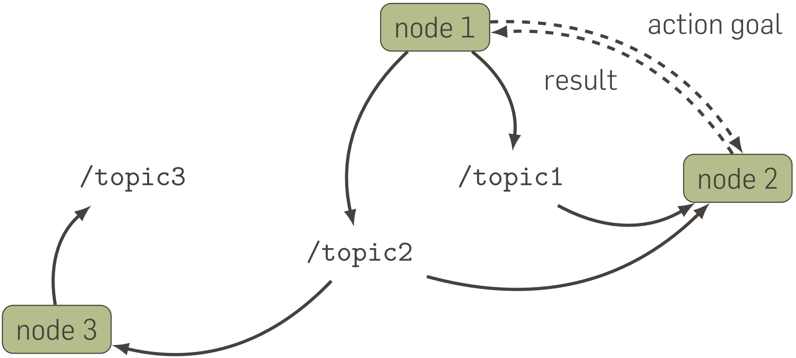
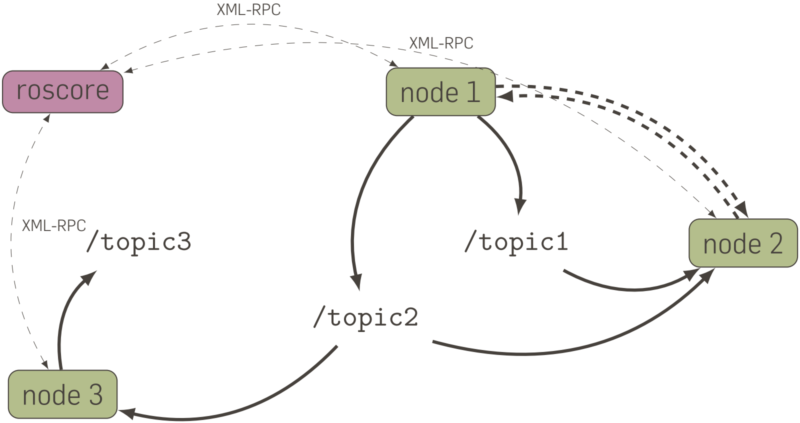


Actions: **asynchronous**

MIDDLEWARES' CORE PRINCIPLE: TALKING NODES



`ROS_MASTER_URI=http://<host>:<port>`

MIDDLEWARES: INTERFACE DEFINITIONS

Interfaces are called **message** in ROS.

Message definitions are the interface definitions in ROS. For example, a 6D pose:

```
$ rosmsg show geometry_msgs/Pose
geometry_msgs/Point position
  float64 x
  float64 y
  float64 z
geometry_msgs/Quaternion orientation
  float64 x
  float64 y
  float64 z
  float64 w
```

MIDDLEWARES: INTERFACE DEFINITIONS

An image:

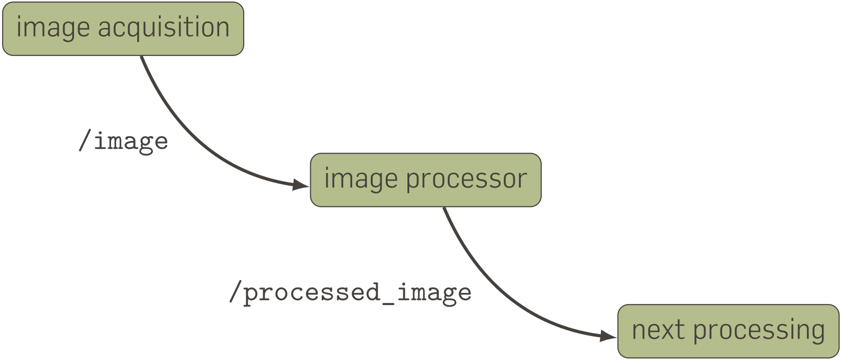
```
$ rosmsg show sensor_msgs/Image
std_msgs/Header header
    uint32 seq
    time stamp
    string frame_id
uint32 height
uint32 width
string encoding
uint8 is_bigendian
uint32 step
uint8[] data
```

MIDDLEWARES: INTERFACE INSTANTIATION

At run-time, messages are **instantiated** and **published over topics**:

```
$ rostopic echo /camera/image_raw
header:
    seq: 56
    stamp:
      secs: 1449243166
      nsecs: 415330019
    frame_id: /camera_frame
height: 720
width: 1280
encoding: rgb8
is_bigendian: 0
step: 3840
data: [32, 57, 51, 36, 61, 55, 41, 63, 60,...
```

EXAMPLE: A SIMPLE IMAGE PROCESSING PIPELINE



```python
import sys, cv2, rospy
from sensor_msgs.msg import Image
from cv_bridge import CvBridge

def on_image(image):
    cv_image = bridge.imgmsg_to_cv2(image, "bgr8")
    (rows,cols,channels) = cv_image.shape
    cv2.circle(cv_image, (cols/2,rows/2), 50,(0,0,255), -1)
    cv2.imshow("Image window", cv_image)
    cv2.waitKey(3)
    image_pub.publish(bridge.cv2_to_imgmsg(cv_image, "bgr8"))

rospy.init_node('image_processor')
bridge = CvBridge()
image_sub = rospy.Subscriber("image",Image, on_image)
image_pub = rospy.Publisher("processed_image",Image)

while not rospy.is_shutdown():
    rospy.spin()
```

```
$ roslaunch gscam v4l.launch
$ python image_processor.py image:=/v4l/camera/image_raw
$ rosrun image_view image_view image:=/processed_image
```

That’s all, folks!

Questions:
Portland Square A216 or **severin.lemaignan@plymouth.ac.uk**

Slides:
github.com/severin-lemaignan/module-mobile-and-humanoid-robots