Cognitive Robotics

Mirror neurons:
imitation and social behavior

@ G. Gini 2015
Neuroscientist Rizzolati and his colleagues at the University of Parma discovered mirror neurons in 1995. It was an accidental discovery that occurred while conducting research on motor neurons in macaque monkeys.
The experiment

- Electrodes were inserted in the ventral premotor cortex of a macaque to study neurons specialized in the control of hand
- The monkey was allowed to reach and pick up food, and the brain activity recorded
- Some of the recorded neurons had the same activity when the monkey was looking at a person picking up a piece of food
- *Humans have similar mirror neuron system*
Mirror Neurons

- Mirror neurons are cells that fire when a monkey (or person) performs an action or when it views another animal performing that same action.
- Firstly discovered for actions of the hand, then for mouth.
Mirror Neurons properties

- are premotor neurons
- are activated by the observation of a behavior - internally firing the motor neurons of the corresponding behavior
- perform a kind of “simulation” of the observed behavior.
- motor properties of mirror neurons are same as “non-mirror” neurons but sensory properties are different
  - These cells do not fire when monkey sees a graspable object
  - They do fire when monkey sees another monkey (or a person) perform actions relative to the object
• Mirror neurons represent intended actions and goals
  ▪ Cells fire when grasping is real and visible
    • Cells also fire when grasping happens behind an occluding screen, as long as the monkey has seen that there is an object to be grasped behind the screen
    • Some mirror neurons will even fire in response to the sound of an action being performed (e.g. the sound of breaking a peanut shell)
  ▪ Hypothesis: combining the observed and the executed action they allow to understand actions from other subjects
Mouth mirror neurons

- Mirror neurons discovered for the actions of the mouth.
  - Most for ingestion of food or putting something in the mouth
  - Other are activated only for facial communicative expressions (protension of tongue, )
- Hypothesis: a basic system to understand the mouth movements has been used to develop a facial communication system
- As a consequence, communication is not monodirectional but circular
the conclusion?

ACTION
PERCEPTION
INTENTION

are all the same thing as far as the brain is concerned
"Our survival depends on understanding the actions, intentions and emotions of others."

» Dr. Rizzolatti
• By watching another animal perform an action, an animal can emulate a task and potentially understand the intent behind the action.
  ▪ There would be absolutely no need for a mirror neuron system if the animal that possessed them were solitary creatures.
  ▪ mirror neurons allow us to optimize our survival abilities through shared knowledge.
• Many animals are programmed to imitate actions during development.
  ▪ imprinting
Mirror neurons are the source of empathy.

When we see a facial gesture, our brains automatically mirror the face and send a message to the limbic system. Once this emotional reaction has kicked in, we understand the other because we have become the other.
Piaget suggested that babies learn to imitate.

Mirror neurons tell us that babies imitate to learn – from the first hour of their lives.
“Learning control has largely been dominated by approaches that use "top-down" representations for the controlled movement. Most commonly, control is based either on trajectory plans that prescribe the desired state of the movement system as a function of time or in terms of control policies that map a perceived state to an appropriate action. The learning of the trajectory plans or control policies is usually based on optimization approaches and reinforcement learning. It is largely accepted that these methods do not scale well to high dimensional control problems, that they are computationally very expensive, that they are not particularly robust to unforeseen perturbations in the environment, and that it is hard to re-use these representations for related movement tasks”.

Schaal
Consequence for psychology

- The interaction mother-child suggests that babies have an innate capability of inter-subjects engagement.
- Mirror neurons allow the embodied simulation, that is the basis to imitate and to generate representations.
- This is against the current theories from Piaget and Freud that use an egocentric view.
Mouth actions

- Mirror neurons of the mouth are 35% of the mouth motor neurons.
  - In monkeys they activate when observing the experimenter making actions with the mouth.
  - They selectively activate for ingestive actions (85%) and for communicative actions (15%). Neurons that code for ingestive actions activate also when the monkey makes communicative actions.

Why communicative and ingestive actions have the same neural substrate?
- Van Hoof – communicative actions in monkeys derive from the ritualization of ingestive actions used to communicate
- Mac Nelage – verbal communication in humans derives from the mouth movements used to ingest food.

The capability to generate voluntary social signals evolved in humans in a specific cortical area for language.
In humans, functional MRI studies have reported finding areas homologous to the monkey mirror neuron system in the inferior frontal cortex, close to **Broca's area**, one of the hypothesized language regions of the brain.

This has led to suggestions that human language evolved from a gesture performance/understanding system implemented in mirror neurons.

Broca’s Area shows that gestures and language are simultaneous. When we hear a word our action neurons fire. This is called **embodied semantics**.
Why is it easier to have a conversation than to speak a monologue?

Because in a conversation the same neurons fire when we *hear* a word as when we *say* it.
In other words, our brain actually has both sides of the conversation.

We *are* the other person
neurological basis of human self-awareness

2009 Ramachandran —

• "I also speculated that these neurons can not only help simulate other people's behavior but can be turned 'inward'—as it were—to create second-order representations or meta-representations of your own earlier brain processes. This could be the neural basis of introspection, and of the reciprocity of self awareness and other awareness. There is obviously a chicken-or-egg question here as to which evolved first, but... The main point is that the two co-evolved, mutually enriching each other to create the mature representation of self that characterizes modern humans". 
Is this what makes us HUMAN?

• Other animals possess mirror neurons.
• Our highly developed mirror neuron system allows us to perform complicated forms of imitation.
• A biological explanation for empathy?
Learning through imitation: a biological approach to robotics
F. Chersi, IEEE trans Autonomous Mental Development, 4, 3, 2012, p 204-214

• Modelling imitation learning through mirror neurons
  - Considers the experiment on monkeys, “reaching, grasping, bringing to the mouth”
  - Implements the “Chain Model”, a model of the mirror neuron system, on a humanoid robot
  - Imitation of the human for object manipulation

• Integrates perception and learning: learns how to concatenate its motor repertoire to reproduce observed actions.
Example

Activity of 3 mirror neurons – in 3 colors:

**Top**: during the execution of “reaching, grasping, bringing to the mouth”

**Bottom**: during the observation of an experimenter doing the same

At $t=1000$ ms the monkey and the experimenter touch the food
Mirror neurons considered

- There are 2 mirror neurons areas in monkeys and similarly in humans:
  - Area F5 in the **premotor cortex** – they appear to contain the hand motor vocabulary with detailed movements
  - Areas PF - PFG of the **inferior parietal lobule** (IPL) – they contain more abstract vocabulary as grasp or reach
- They code also higher level information as the final goal of the action sequence
- Signals arriving to the IPL correspond to the motor content extracted from the visual input.
- Mirror neurons do not perform directly visual processing.
Chain model

• Hypothesis: *mirror neurons in the 2 cortex areas are organized in chains, encoding the sequence of motor acts that leads to the specific goal.*
• The execution and the recognition of the sequence are the result of the propagation of the activity along specific chains.
• The same mechanism for action execution is used for executing – the mirror neurons behave like motor neurons – and for observation - the mirror neurons resonate when the observer sees the corresponding motor action.
• The prefrontal cortex, which encodes intentions, implements the early chain selection mechanism
Fig. 2. Scheme of the fronto-parietal circuit with two neural chains. Each neuronal pool in the chains receives input from the preceding and projects to the following pool, moreover it is connected to the motor areas, and receives from sensory areas. The prefrontal area contains the intention pools ("Eating" and "Placing") which integrate the information from sensory areas and then provide the activating input to the chains.
Chain model

- The execution is the result of propagating the activity along specific chains.
- In the figure,
  - The first activated area is reaching; it propagates to premotor and motor cortex that transmit it to the spinal cord; it also propagates to the next motor action.
  - This pool does not immediately fire because it needs more input from sensory and proprioceptive areas.
  - Each area also backpropagates to “confirm” the action.
• Two condition, mirror and motor.
• Two tasks, *placing* or *taking*
• In mirror, a monkey has to observe an experimenter reaching and grasping either a piece of food or a metal cube and then either put it into the mouth or placing into a container.
• In motor the monkey has to execute the described actions
robot experiment

• Substitute food and object with 2 colored objects: yellow for food and red for object. The container is the green area. The mouth is replaced by a position near the stomach.
implementation

• (considering only 1 IPL chain).
• Can set the robot in idle or learning mode
• Vision and control — not bioinspired but classical methods
  ▪ Vision:
    • background model to estimate the probability that a pixel is part of the background or not
    • Color classification — use a lookup table
    • Storage of hand postures to use
    • Camera is calibrated
    • Log polar representation is used for objects
Recognition of motor acts

- At each time information about the hand posture and position is available from vision.
- Motor acts to recognize are:
  - Reaching: hand open and distance to object decreasing
  - Grasping: hand near the object and shape varies
  - Placing: hand at grasping distance and approaching the place
  - Taking: hand closed at grasping distance and distance decreasing from the demonstrator
Neural network configuration

- 3 layers:
  - Prefrontal - where goals are encoded
  - Parietal - where sequences are recognized
  - Premotor - which dispatches the motor commands
- Each layer contains pools of 100 identical neurons
  - 80 excitatory, 20 inhibitory
  - Randomly connected to 20% neurons in the same pool; excitatory also connected to 2% of the neurons of other pools
- Each prefrontal pool encodes only one goal (taking or placing) – 4 pools for each
- Each parietal and premotor pool encodes only one motor act (reaching, grasping, etc) -10 pools for each act
- Connections between parietal and premotor layer are genetically predermined, while connections between parietal neurons and parietal and prefrontal are learned.
Network organization

Pools are initially connected at random, but after learning they form the correct chain.

The connection between prefrontal and parietal cortex neurons are predetermined.
Connections between parietal and prefrontal neurons are learned.
Spiking neuron model

- “Integrate and fire” mode for each neuron
  - VT is the membrane potential
  - VL is the resting potential
  - CM is the membrane capacity
  - Itot is the synaptic current

\[
C_m \frac{dV(t)}{dt} = -g_L(V(t) - V_L) + I_{tot}(t)
\]

- when VT reaches the threshold a spike is generated and propagated and the membrane potential is reset to VL.

- The total input to a neuron is

\[
I_{tot}(t) = \sum_{i \in \text{pool}} W_{i,n} \cdot \delta(t - t_i) + \sum_{j \in \text{prev}} W_{j,n} \cdot \delta(t - t_j) + \sum_{k \in \text{ext}} W_{k,n} \cdot \delta(t - t_k)
\]

Win from same pool
Wjn from previous pool
Wkn from sensors and motor areas
Learning rule

- The experimenter shows the actions
- Learning modifies the weights between neurons in 2 different pools
- The synaptic efficacy between 2 neurons is reinforced if the postsynaptic neuron fires shortly after the presynaptic neuron (8 to 10 ms), weakened if the presynaptic fires after the postsynaptic.
- 40 training epochs are used
Fig. 12. Three frames extracted from the “grasping to take” sequence executed by the robot. “Taking” consists in placing the object into the box inside the robot.

Fig. 13. Three frames extracted from the grasping to place sequence executed by the robot.
conclusions

- In this system the goal of the action is explicitely embedded in the system through the use of chains
- Recognition and execution utilize the same neural circuit
- After training, the system shows no errors in execution
Information encoding in brain

- Cognition is separated from sensor-motor system, but is managed by the same neural population

1. **Normalization**: neural responses are divided by the summed activity of a neural population

2. **Population coding**: neighboring neurons have similar activity
3. **Gain modulation**: one input affects the sensitivity of the neuron to the other input without modifying its selectivity.

4. **Neuroplasticity**: the ability to reorganize neural pathways in response to changes in the environment.

5. **Statistical coding**: a specific kind of population coding; reduce dimensionality of the input space.
Other models for Imitation learning

PASSIVE

ACTIVE

DUAL-ROUTE
## Passive imitation

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- The motor system is only called at the end.
Passive imitation

Demonstrator

Visual information

Postures estimation

Postures stream

Representative postures extraction

Imitator

Actuators

Matching module

Target posture

Posture queue

Self posture estimation

Current posture

Memory
Passive imitation is universal for every problem?

2 limitations:

- No distinction between "known" and "new"
- The motor system is only called at the end
Active imitation

- the motor system is always activated

- Perception and action generation are coupled

- Imitation is an active and predictive process.
  - The imitator generates behaviours in parallel with perception.

- it can be difficult to imitate movements not present in the set of known movements
**Active imitation**

- **State information**
  - Demonstrator’s state if in perception mode
  - Own state if in generation mode

- **Target goal** (optional)

- **Motor System**

- **Forward model**
  - Prediction for t+1
  - Comparison
  - Motor commands
  - Proprioceptive feedback

- **Behaviour**
  - t
  - t+1

- **Error**
Complete active imitation

- **Behaviour 1**: Forward Model (of body parts relevant to Behaviour 1)
  - Prediction for t+1
  - Comparison
  - Error

- **Behaviour 2**: Forward Model (of body parts relevant to Behaviour 2)
  - Prediction for t+1
  - Comparison
  - Error

- **Behaviour N**: Forward Model (of body parts relevant to Behaviour N)
  - Prediction for t+1
  - Comparison
  - Error

- **Motor System**: Proprioceptive feedback

State information:
- t

Motor commands:
- t

- t+1
Combining passive and active

In case the demonstrator uses behaviors not known by the imitator?

All the available behaviors have confidence zero, so are not apt for imitation

In this case it is necessary to learn a new behavior

**dual-route architecture**
**dual-route**

**Demonstrator**

- Visual information

**Imitator**

- Signal if no behaviour predicts sufficiently well
- Prediction of next state

**Generative Component**

- Reinforcement

**Learning Component**

- Store new behaviour
Open questions for imitation:

- What skills should be ‘innate’ in our robots?
- How should these behaviors be combined to develop more complex behaviors?
- What learning strategies are useful and when?
- How do we motivate our robots?
- Can developmental algorithms be simpler than other methods of programming robots?
Classical learning methods

- Supervised learning
  - classification, regression

- Unsupervised learning
  - clustering, dimensionality reduction

- Reinforcement learning
  - generalization of supervised learning
  - learn from interaction with the environment to achieve a goal

Diagram:
- Environment
- Agent
- Action
- Reward
- New state
Reinforcement learning

- Learning what to do without a teacher
  - it receives a reward or reinforcement from the action
  - learn from the reward an optimal policy
- Task
  Learn how to behave successfully to achieve a goal while interacting with an external environment
  - Each percept(e) is enough to determine the State
  - The agent task is to find a optimal policy, mapping states to actions, that maximize long-run measure of the reinforcement
  - Can be modeled as Markov Decision Process model
Statistical learning theory

- A framework to study the problem of inference
- Vapnik: A theory of inference should be able to give a formal definition of words like learning, generalization, overfitting, and also to characterize the performance of learning algorithms…

- The process of inductive learning has the steps:
  - Observe a phenomenon
  - Construct a model
  - Make predictions using this model

  *Machine learning - automate it*
  *Learning theory - formalize it*

- Many ways to do it
- No universally best choice
Among the many functions that can accomplish the task of inducing a model, we need to quantify their characteristics, as performance and simplicity. “no free lunch theorem” - a popular name to indicate the practical results of theorems demonstrated by Wolpert in 1997 and stating that any two models are equivalent when their performance is averaged across all possible problems. We need assumptions on the phenomenon to study, otherwise there is no better algorithm.

- Given a distribution, what is the model?
New view on robot learning

- Developmental robotics - Epigenetic robotics - Autonomous mental development
  - Investigates models coming from developmental psychology or developmental neuroscience
  - (a) embodiment of the systems;
  - (b) situatedness in physical and social environments;
  - (c) developmental process through which varied and complex cognitive and perceptual structures emerge as a result of the embodied system interacting with its physical and social environment.
“Mental development is a process during which a brain-like natural or artificial embodied system, under the control of its intrinsic species-specific developmental program, develops mental capabilities through its real-time interactions with its environments using its own sensors and effectors.”

- Many different studies about
  - Social interaction
  - Sensorimotor control
  - Categorization
  - Motor skill acquisition
Combining developmental psychology and robotics, and:
(a) embodiment of the systems;
(b) situatedness in physical and social environments;
(c) a prolonged developmental process through which varied and complex **cognitive and perceptual structures emerge as a result of the embodied system** interacting with its physical and social environment.

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**Epigenetic**

Combining developmental psychology and robotics, and:
(a) embodiment of the systems;
(b) situatedness in physical and social environments;
(c) a prolonged developmental process through which varied and complex **cognitive and perceptual structures emerge as a result of the embodied system** interacting with its physical and social environment.
• **Manual development**
  - **Given:** Task T and ecological conditions Ec
    - Human developer H understands T and programs the agent: \( A = H(T, Ec) \)
  - Task specific architecture, representation and skills are developed by humans

• **Autonomous development**
  - **Given:** Ec, the task is unknown; internal representation can not be predefined
    - Human developer H writes a task-non specific developmental program for the newborn agent: \( A(0) = H(Ec) \)
    - The task has to be understood by the agent itself
  - **After teachers can affect the behavior of the robot by:**
    - Supervised learning
    - Reinforcement learning
    - Communicative learning
Change of view

- the task is not given to the developer
  Human can only adjust the behavior by teaching
- Only way to control robots in unknown domains

- Engineering rationales
  - Making programming robots easier

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Open questions for development:

- Can epigenetic robotics provide true animal-like intelligence (“strong AI”)?
- Is consciousness necessary for complex cognitive development?
- What skills should be ‘innate’ in our robots?
- How should these behaviors be combined to develop more complex behaviors?
- What learning strategies are useful and when?
- How do we motivate our robots?
- Can developmental algorithms be simpler than other methods of programming robots?
- What are the practical applications?
Cognition from Bottom-up

- Categorization, perception, memory turn out to be directly coupled to sensory-motor processes and thus to embodiment.
- Rather than starting from representations of objects, we propose to start representing the very basis: the agent's body and its low-level interaction with the environment.
- Any cognitive processing will always be mediated by the body and the sensory-motor loops. Therefore, these are the first candidates for an agent to learn about.

• 2006 Minsky complained:
  ▪ central problems, like commonsense reasoning, neglected
  ▪ majority of researchers pursued commercial applications
    • e.g. commercial applications of neural nets or genetic algorithms

"So the question is why we didn't get HAL in 2001?
I think the answer is I believe we could have"