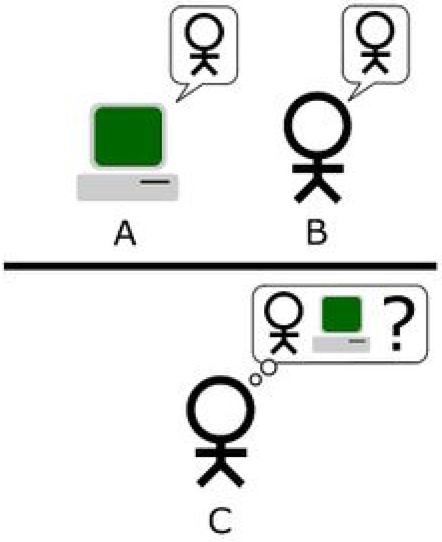
Week 1: Introduction to Developmental Robotics

10.02.2016

AI Origins

"*Instead of trying to produce a programme to simulate the adult mind, why not rather try to produce one which simulates the child's? If this were then subjected to an appropriate course of education one would obtain the adult brain*" Alan Turing (1950:440).



Definition

"Developmental Robotics is the interdisciplinary approach to the autonomous design of behavioral and cognitive capabilities in artificial agents (robots) that takes inspiration from the developmental principles and mechanisms in natural cognitive systems (children)" (Cangelosi & Schlesinger, 2015)

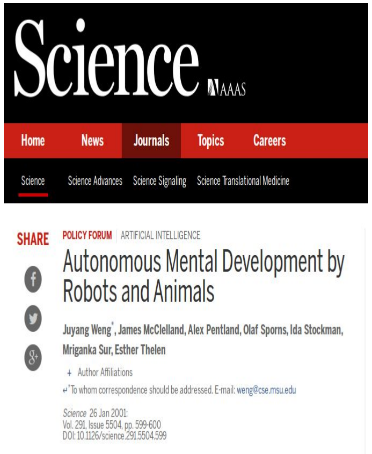
DevRob Characteristics

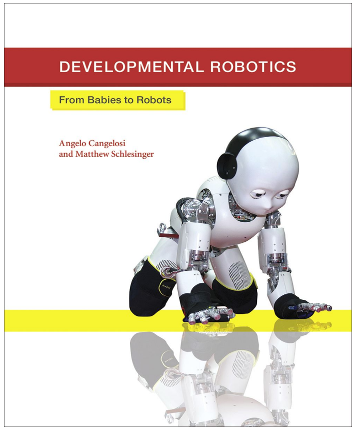
- Highly **interdisciplinary** effort of empirical developmental sciences, e.g. **developmental** psychology, neuroscience and comparative psychology, and **computational** and **robotics sciences**, e.g. robotics and artificial intelligence.
- Developmental sciences provide the **empirical bases** and data to identify the general developmental principles, mechanisms, models and phenomena guiding the incremental acquisition of cognitive skills.
- The implementation of these principles and mechanisms into a robot's control architecture and the **testing through experiments**, where the robot interacts with its physical and social environment simultaneously, permits the **validation** of such principles and the actual design of complex behavioral and mental capabilities in robots.

DevRob History and Origins

- **Pioneering publications** advocating and explicit link between human development and robotics;
- Sandini, Metta and Konczak (1997): “some of the **peculiarities of human sensori-motor development** for the execution of visually guided reaching and to suggest a **similar framework for the implementations of artificial systems** able to adapt to changes in sensory and biomechanical constraints. In particular the problem of mapping sensory information into direct motor commands will be presented and the advantages of a **closer synergy between the study of artificial systems and neurosciences** will be discussed”
- Brooks et al. (1998): “Using evidence from cognitive science and neuroscience, we suggest four alternative essences of intelligence to those held by classical AI. These are the parallel themes of **development, social interaction, embodiment, and integration**.”
- Scassellati (1998): This paper advocates a developmental approach to building complex interactive behaviors for robotic systems. A developmental methodology is advantageous because it provides a structured decomposition of complex tasks, because it facilitates learning, and because it allows for a gradual increase in task complexity. And idea of re-use
- Asada, MacDorman and Kuniyoshi (2001): This paper proposes **cognitive developmental robotics** (CDR) as a new principle for the design of humanoid robots. This principle may provide ways of understanding human beings that go beyond the current level of explanation found in the natural and social sciences. Furthermore, a methodological emphasis on humanoid robots in the design of artificial creatures holds promise because they have many degrees of freedom and sense modalities and, thus, must face the challenges of scalability that are often side-stepped in simpler domains.

DevRob Terminology





Other names proposed for the same approach/field;

- Cognitive Developmental Robotics (Asada et al. 2001, 2009) for more general cognitive systems approach;
- Autonomous Mental Development (Weng et al. 2001; ICDL Conference series) to stress autonomous aspects of mental (i.e. cognitive) development;
- Epigenetic Robotics (Balkenius, Zlatev, Kozima, Dautenhahn & Breazeal, 2001; Berthouze & Ziemke, 2003; EpiRob Conference Series) to trace its origins and inspiration from Piaget's Epigenetic Theory.
  - Development proceeds through an ordered succession of stages that are guided, but not determined by the genes, where higher stages require more time and experience than the lower ones.

Most recent and comprehensive review by Cangelosi and Schlesinger

DevRob History and Origins

- The birth of developmental robotics field traces its origins to the years 2000-2001, in coincidence with two scientific workshops/conference series:
  - **ICDL: International Conference on Development and Learning** (first ICDL Workshop in 2000, in Lansing);
  - **EpiRob: International Workshop on Epigenetic Robotics** (first EpiRob Workshop in 2001, in Lund, Sweden)
- The two conference series merged efforts in 2011 with **IEEE Joint ICDL-EpiRob Conference** (Frankfurt) and subsequent yearly meetings
- Dedicated journal
  - from 2009: IEEE Transactions on Autonomous Mental Development
  - from 2016: IEEE Transactions on Cognitive and Developmental Systems
- icdl-epirob.org
- 2018@Turkey?

Developmental Theories

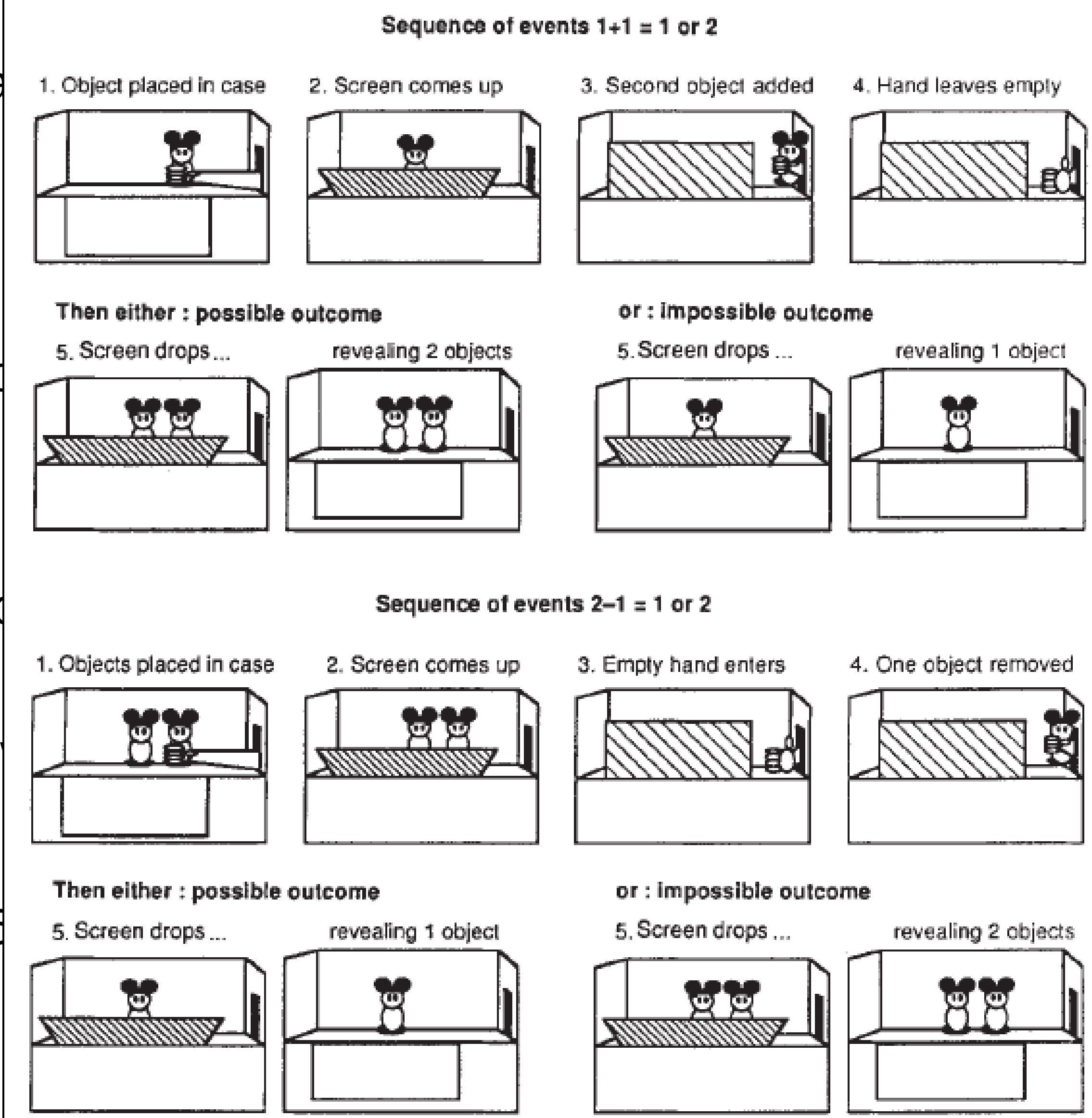
Developmental Theories and Na
debate informs DevRob field.

Nativist (Nature) Theories:

- Children are born with **innate, d**
  of direct influence of the genes c
  influence from environment.

Examples:

- Chomsky (1956): children are bo
  language;
- Leslie (1994): children are born
- Wynn (1998): innate knowledge
  - Look more to unexpected 5



NATURE · VOL 358 · 27 AUGUST 1992

Developmental Theories

Empiricist (Nurture) Theories:

- Importance of the **social and cultural environment and experience** on cognitive development.

Examples:

- **Tomasello** (2003) principle of constructivist and emergent development, whereby the child constructs her own language competence through interactions with others
- **Piaget**'s (1971) **Epigenetics** theory, based on adaptation (assimilation and accommodation) with stage-like, qualitative progression.
- Thelen and Smith's (1994) dynamical systems theory of development. This considers complex, dynamics interaction of various neural, embodiment and environmental factors in the self-organization of cognitive strategies;

The nature/nurture debate and nativist/empiricist theories have significantly influenced other fields interested in the study of intelligence, specifically in artificial intelligence and robotics.

DevRob Principles

The six general principles that inform the work of DevRob.

Principles	Characteristics
1 Development as a Dynamical Systems	Decentralized system Self-organization and emergence Multicausality Nested timescales
2 Phylogenetic and Ontogenetic Interaction	Maturation Critical period Learning
3 Embodied and Situated Development	Embodiment Situatedness Enaction Morphological computation Grounding
4 Intrinsic Motivation and Social Learning	Intrinsic motivation Value systems Imitation
5 Non-linear, Stage-Like Development	Qualitative stages U-shape phenomena Bootstrapping
6 Online Open-Ended Cumulative Learning	Online learning Cumulative Cross-modality Cognitive bootstrapping

DevRob Principles

Principle 5: Non-linear, stage-like development

- Development does not consist in the linear, incremental improvement of skills, but rather it often shows non-linear trends based around qualitative, sudden changes in performance (stages).
- For example, the key tenet of Piaget‘s theory is that a child goes through different stages of development, where at each stage the infant develops qualitatively-different and increasingly-complex schemas, the building block of intelligence. Stages are influenced by maturational constraints, determined by genetic influence, and called "epigenetics" in Piaget’s Theory (Piaget, 1971).

DevRob Principles

Principle 5: Non-linear, stage-like development

- Piaget's four stages of the development of mental capabilities, and abstract thought schemas from sensorimotor knowledge.

- Sensorimotor Stage (Stage 1, 0-2 years), with the acquisition of sensorimotor schemas, e.g. motor reflexes;
  - Reflex acts (m1), primary circular reactions (m1-m4), secondary circular reactions (m4-m8), coordinated secondary schemes (m8-m12)
- Preoperational Stage (Stage 2, 2-7 years), children acquire egocentric symbolic representations of objects and actions, to **represent** objects
- Concrete Operational Stage (Stage 3, 7-11 years) to adopt other people's perspectives on object representation and perform mental transformation operations on concrete objects (e.g. liquid conservation task);
- Formal Operational Stage (Stage 4, 11+ years) with full abstract thinking capabilities and complex problem solving.

DevRob Principles

Principle 5: Non-linear, stage-like dev.

- Piaget's four stages of the development of mental capabilities, and abstract thought schemas from sensorimotor knowledge.
- Sensorimotor Stage (Stage 1, 0-2 years), with the acquisition of sensorimotor schemas, e.g. motor reflexes;
  - Reflex acts (m1), primary circular reactions (m1-m4), secondary circular reactions (m4-m8), coordinated secondary schemes (m8-m12)
- Preoperational Stage (Stage 2, 2-7 years), children acquire egocentric symbolic representations of objects and actions, to represent objects
- Concrete Operational Stage (Stage 3, 7-11 years) to adopt other people's perspectives on object representation and perform mental transformation operations on concrete objects (e.g. liquid conservation task);
- Formal Operational Stage (Stage 4, 11+ years) with full abstract thinking capabilities and complex problem solving.

DevRob Principles
Principle 5: Non-linear, stage-like dev.

- Piaget's four stages of the development of mental capabilities, and abstract thought schemas from sensorimotor knowledge.

- Sensorimotor Stage (Stage 1, 0-2 years), with the acquisition of sensorimotor schemas, e.g. motor reflexes;
  - Reflex acts (m1), primary circular reactions (m1-m4), secondary circular reactions (m4-m8), coordinated secondary schemes (m8-m12)
- Preoperational Stage (Stage 2, 2-7 years), children acquire egocentric symbolic representations of objects and actions, to represent objects
- Concrete Operational Stage (Stage 3, 7-11 years) to adopt other people's perspectives on object representation and perform mental transformation operations on concrete objects
- Formal Operational Stage (Stage 4, 11+ years) with full abstract thinking capabilities and complex problem solving.

DevRob Principles

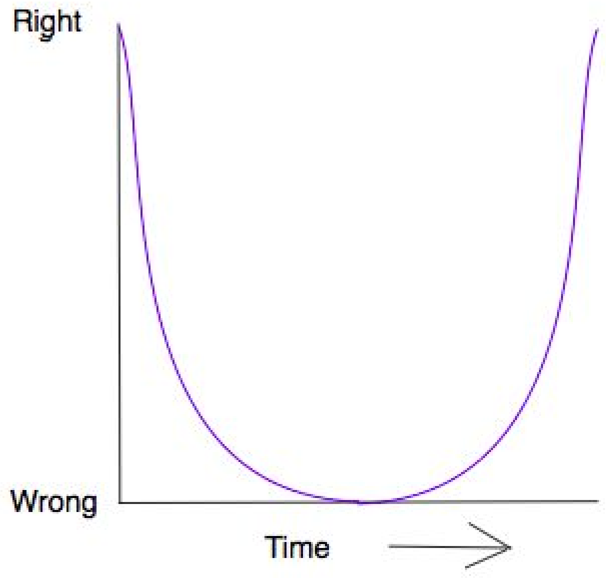
Principle 5: Non-linear, stage-like dev.

- Piaget's four stages of the development of mental capabilities, and abstract thought schemas from sensorimotor knowledge.
- Sensorimotor Stage (Stage 1, 0-2 years), with the acquisition of sensorimotor schemas, e.g. motor reflexes;
  - Reflex acts (m1), primary circular reactions (m1-m4), secondary circular reactions (m4-m8), coordinated secondary schemes (m8-m12)
- Preoperational Stage (Stage 2, 2-7 years), children acquire egocentric symbolic representations of objects and actions, to represent objects
- Concrete Operational Stage (Stage 3, 7-11 years) to adopt other people's perspectives on object representation and perform mental transformation operations on concrete objects
- Formal Operational Stage (Stage 4, 11+ years) with full abstract thinking capabilities and complex problem solving.

DevRob Principles

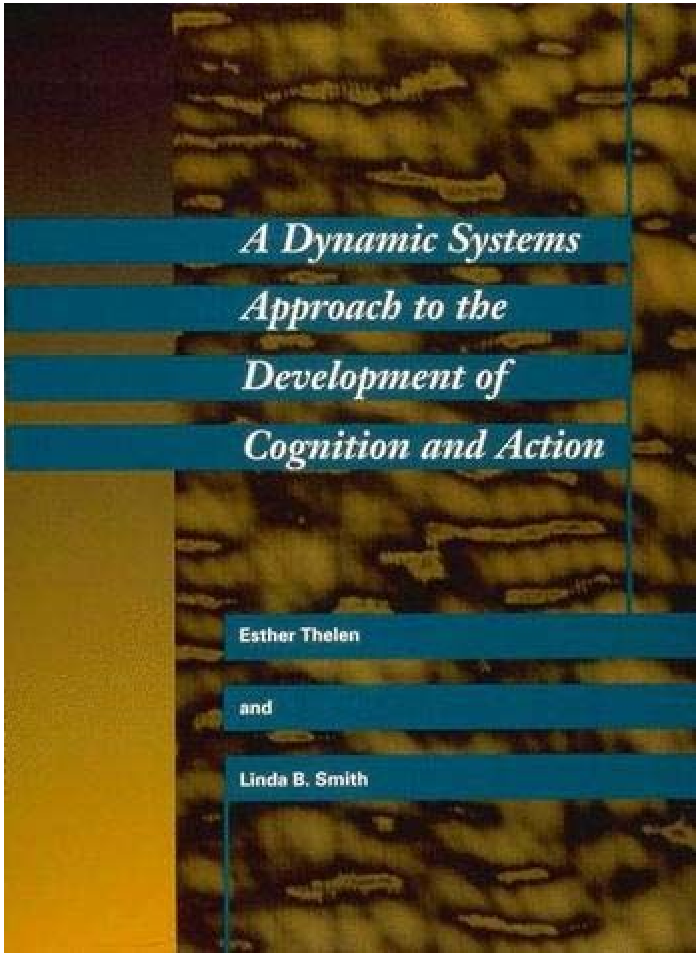
Principle 5: Non-linear, stage-like dev.

- U-Shape phenomenon The (inverted) U-shape phenomenon is an example of such non linearity. This is characterized by an early stage of good performance and low errors, followed by an unexpected decrease in performance, which is subsequently recovered to show high performance.
- In language learning: a child begins to use the verb ‘spoke’, subsequently, she may use instead ‘speaked’, and, later and finally, she again uses ‘spoke’



DevRob Principles
Principle 1: Development as a Dynamical System

- Thelen and Smith (1994) propose that the development of a child should be viewed as **change within a complex dynamic system**, where the growing child can generate novel behaviors through its interaction with the environment, and these behavioral states vary in their stability within the complex system. Development as the emergent product of the intricate and dynamic interaction of many decentralized and local interactions related to the child's growing body, brain, and environment.



DevRob Principles

Principle 1: Development as a Dynamical System

Development as a Dynamical System: **Nested Timescales**, i.e. neural and embodiment phenomena acting at different timescales, and all affecting development in an intricate, dynamical way.

- For example?

DevRob Principles

Principle 1: Development as a Dynamical System

A-not-B Error Experiment. Why? This child psychology experiment demonstrates the combined effects of the concepts of multicausality and nested timescales

Inspired by Piaget's object permanence experiment, when one toy is repeatedly hidden under a lid at a location A (right) during the first part of the experiment. Towards the end of the task, the experimenter hides the same toy in the location B (left) for a single trial, and then asks the child to reach for the object

- Whilst infants older than 12 months have no problem in reaching for the toy in its correct location B, unexpectedly most 8- to 10-month-old infants produce the curious error of looking for the object in the location A. This error is only produced when there is a short delay between hiding and reaching.

DevRob Principles

Principle 1: Development as a Dynamical System

A-not-B Error Experiment

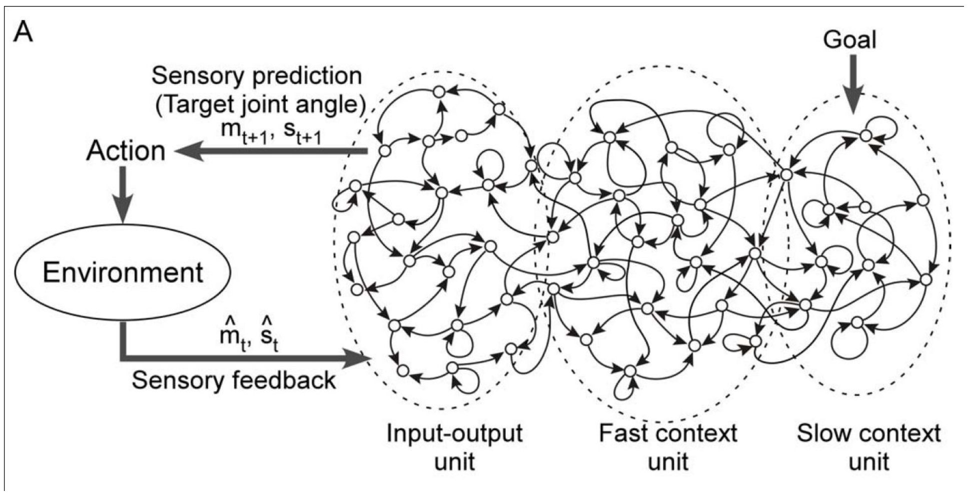
- Whilst psychologists such as Piaget have used explanations based on age (stage) differences linked to qualitative changes in the capability to represent objects and space, a computational simulation of the dynamical system model (Thelen, Schöner, Scheier & Smith, 2001) has demonstrated that there are many decentralized factors (multicausality) and timing manipulations (nested timing) affecting such a situation.
- These for example depend on the time delay between hiding and reaching, the properties of the lids on the table, the saliency of the hiding event, the past activity of the infant and her body posture. The systematic manipulation of these factors results in the appearance, stopping and modulation of the A-not-B errors.

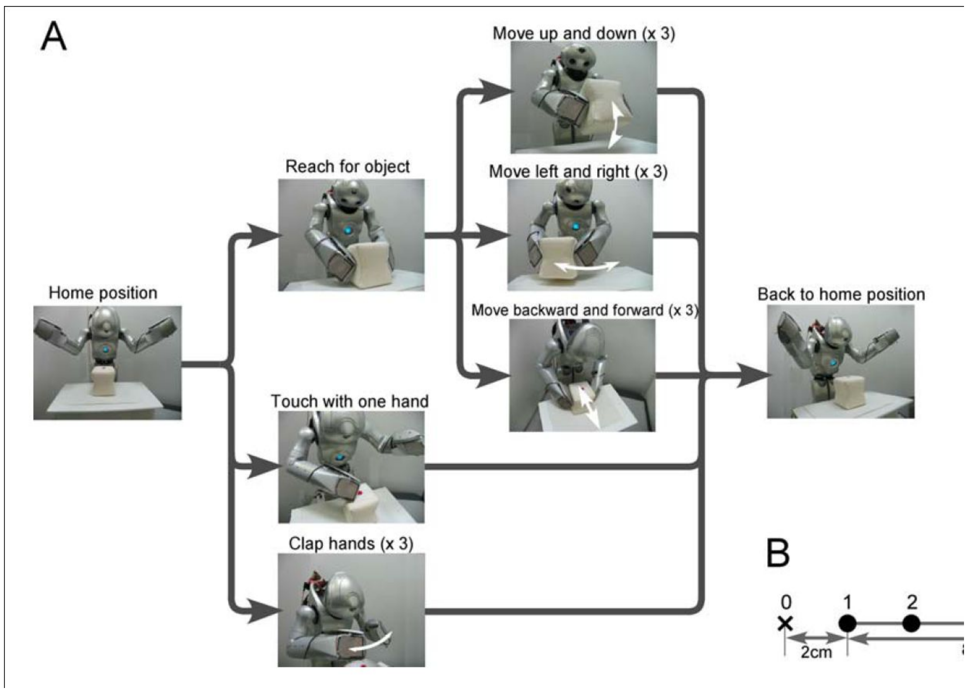
DevRob Principles
Principle 1: Development as a Dynamical System

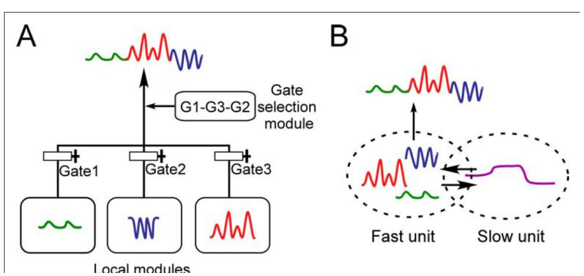
Development as a Dynamical System: **Multicausality** when one behavior is determined by the simultaneous and dynamic consequences of various phenomena at the level of the brain, body, and environment. Example of dynamic changes in crawling and walking behaviors as multicausality changes in the child's adaptation to the environment, in response to body growth changes

DevRob Principles

Principle 1: Development as a Dynamical System





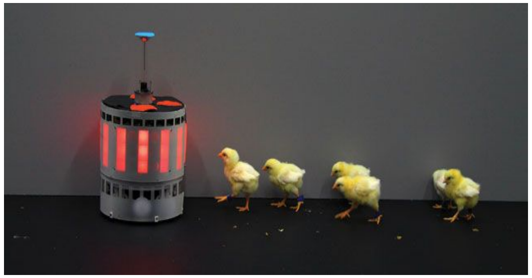


Yamashita, Yuichi, and Jun Tani. "Emergence of functional hierarchy in a multiple timescale neural network model: a humanoid robot experiment." PLoS Comput Biol 4.11 (2008): e1000220.

DevRob Principles

Principle 2: Phylogenetic and Ontogenetic Interaction

- Brain maturation → decrease in plasticity, gradual hemispheric specialization, pruning of neurons and connections
- Critical periods: the time frames when organism is more sensitive to env, and therefore can efficiently learn. After critical period..
- One example: imprinting - only possible within the few hours and last long.



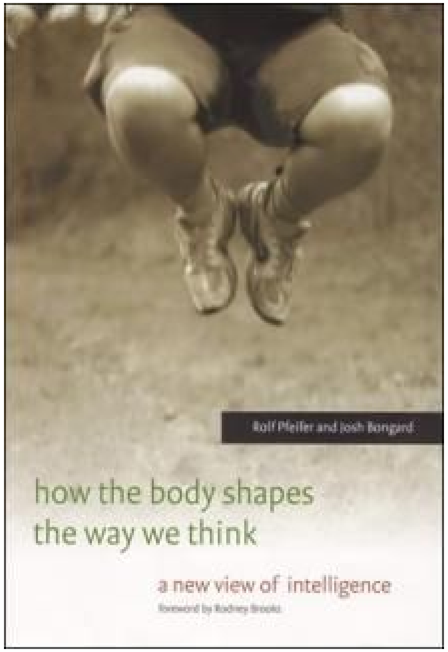
Konrad Lorenz

DevRob Principles

Principle 3: Embodied, Situated and Enactive Development

"Intelligence cannot merely exist in the form of an abstract algorithm but requires a physical instantiation, a body". (Pfeifer & Scheier 1999) The body of the child (or of the robot), and its interaction with the environmental context determines the type of representations, internal models and cognitive strategies learned:

- Embodiment: Fundamental role of the body in cognition and intelligence (Embodied/grounded cognition);
- Situatedness: Role of interaction between the body and its environment;
- Enaction: the organism's autonomous generation of a model of the world through sensorimotor interactions.



DevRob Principles

Principle 3: Embodied, Situated and Enactive Development

- **Morphological computation** (Pfeifer & Bongard, 2007)
- The organism can exploit the body's morphological properties (e.g. type of joint, length of limbs, passive/active actuators), and the dynamics of the interaction with the physical environment (e.g. gravity) to produce intelligent behavior.
- The exploitation of morphological computation has important implications for energy consumption optimization in robotics, and for the use of increasing use of compliant actuators and soft robotics material (Pfeifer, Lungarella & Lida, 2012).

DevRob Principles

Principle 3: Embodied, Situated and Enactive Development

- **Morphological computation** (Pfeifer & Bongard, 2007)
- The organism can exploit the body's morphological properties (e.g. type of joint, length of limbs, passive/active actuators), and the dynamics of the interaction with the physical environment (e.g. gravity) to produce intelligent behavior.
- The exploitation of morphological computation has important implications for energy consumption optimization in robotics, and for the use of increasing use of compliant actuators and soft robotics material (Pfeifer, Lungarella & Lida, 2012).

DevRob Principles

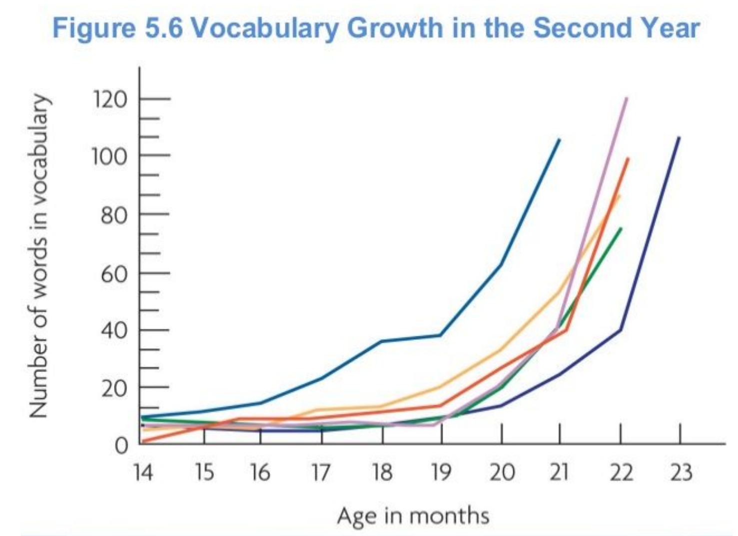
Principle 4: Intrinsically motivated learning

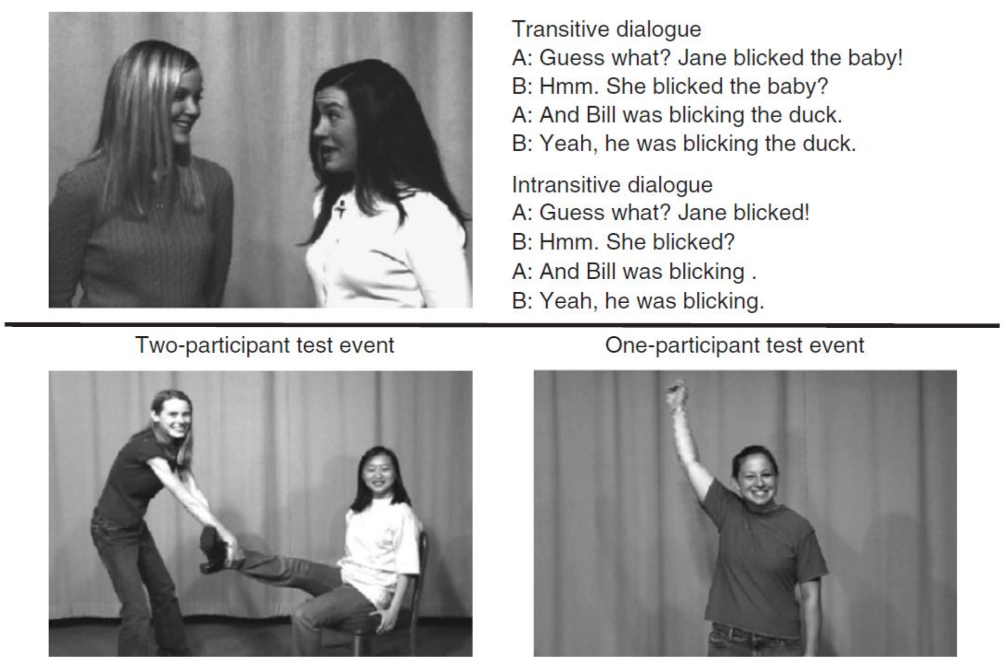
- Not to achieve goals, target, satisfy needs
- Learn to learn

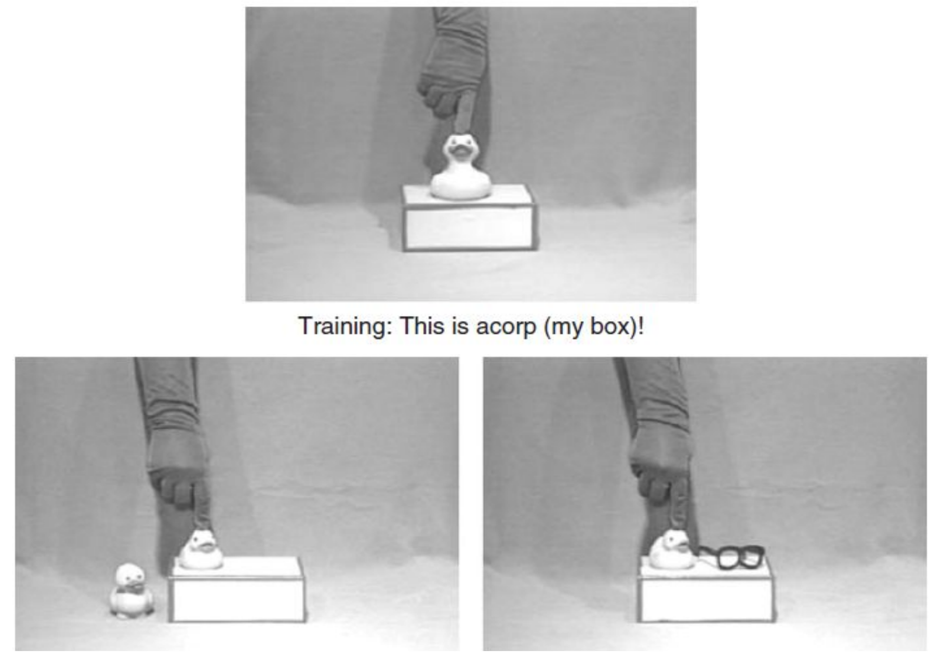
DevRob Principles

Principle 6: Open-ended cumulative

- Vocabulary spurt
  - Syntactic & semantic bootstrapping







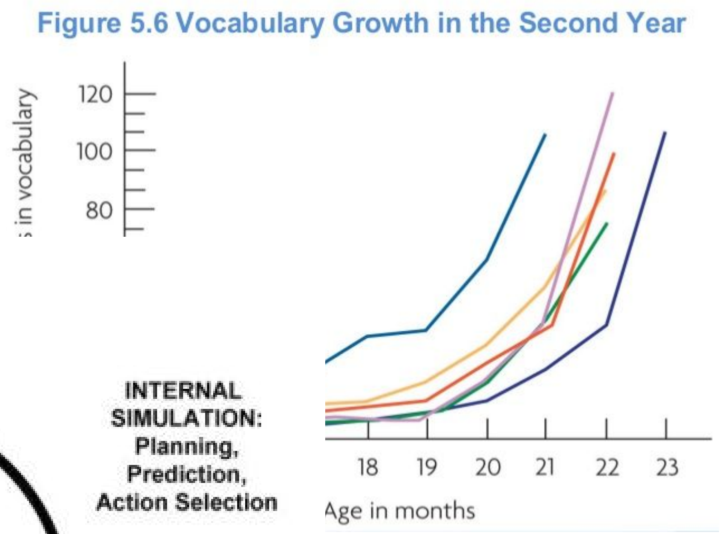
Scott RM, Fisher C. 2-year-olds use distributional cues to interpret transitivity-alternating verbs. Lang Cogn. Process 2009, 24:777–803.

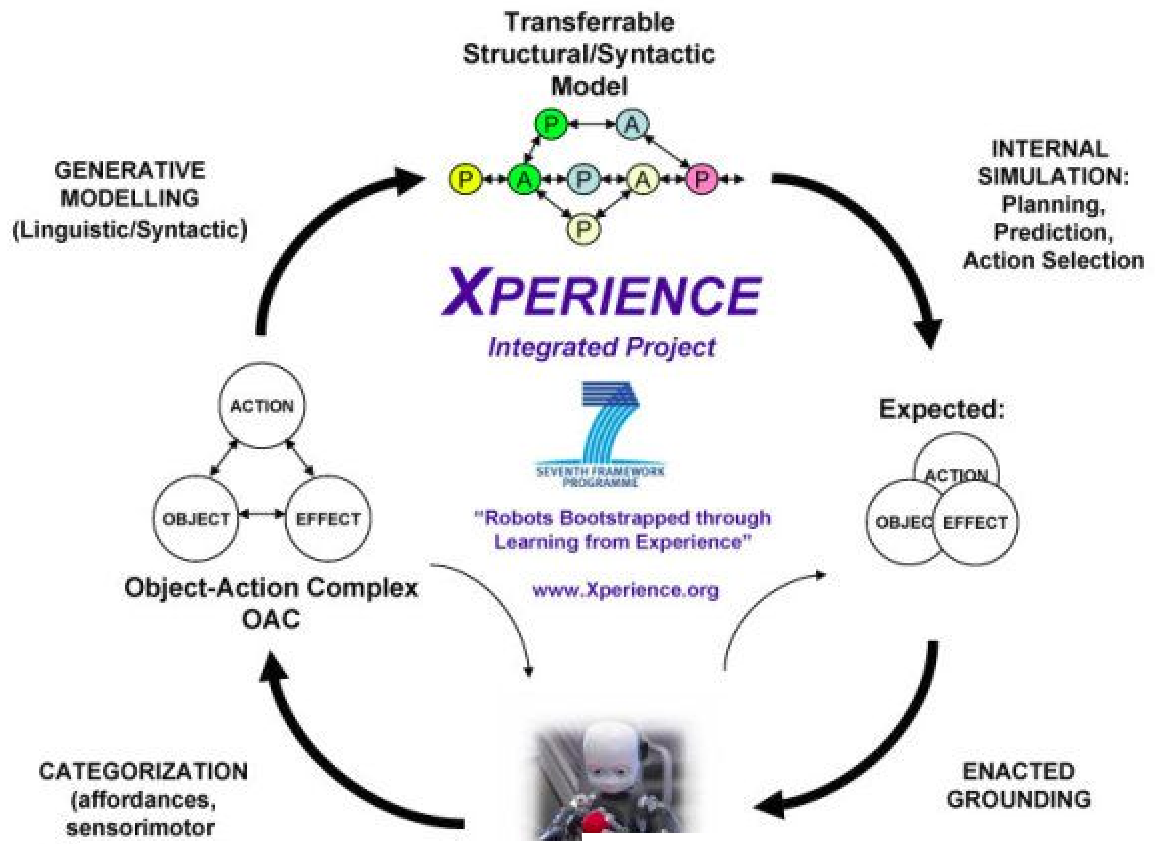
Fisher C, Klingler SL, Song H. What does syntax say about space? 26-month-olds use sentence structure in learning spatial terms. Cognition 2006.

DevRob Principles

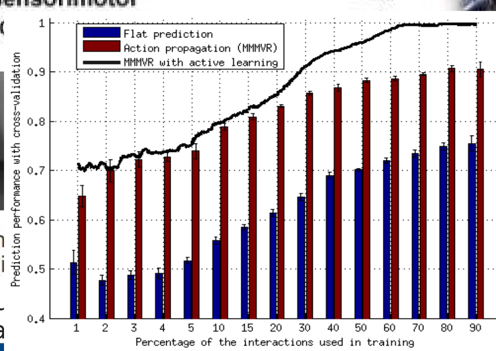
Principle 6: Open-ended cumulative

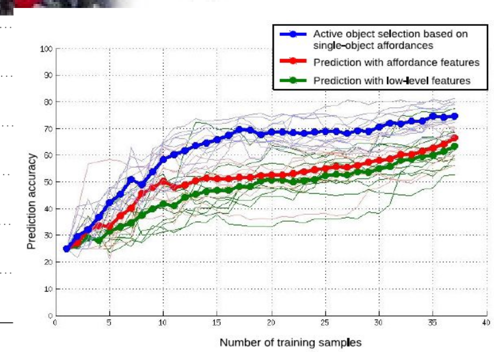
- Vocabulary s
  - Syntacti



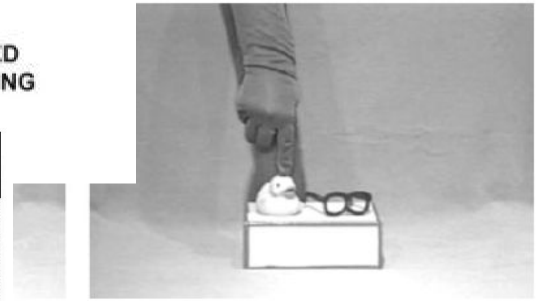


Two-participant test e





ɔ (my box)!



Location match screen

Experimental con
Control condi

box)! What else is acorp (my box?)

Scott RM, Fisher C. 2-year-olds u
transitivity-alternating verbs. La

loes syntax say about space? 26-month-
ing spatial terms. Cognition 2006.