Artificial Life
Summer 2015

Roots of Complex Behavior
&
Braitenberg Vehicles

Master Computer Science [MA-INF 4201]
Mon 8:30 – 10:00, LBH, Lecture Hall III.03a

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Roots of Complex Behavior

- Ideas from biology and from engineering
- Control architectures
- Reactive control
- Proactive control
- SMPA architecture
- Some systems theory
- Braitenberg vehicles
  - Type 1
  - Type 2
  - Type 3
  - Type 3b based obstacle avoidance
  - Type 4
  - Type 5 - 14

Ideas from biology and engineering

Trying to build systems that behave like the systems we can find in living nature (e.g. animals) has been an idea and a challenge throughout the last years, the last decades and the last centuries.

The state-of-the art in control architectures has progressed tremendously during the last 5-10 years,

but still,

the results are by no means comparable to the capabilities of even simple animals.

Control Architectures

Today a variety of control architectures exits.

Some of them have been inspired by living nature, or have tried to copy aspects from the biological role model.

Other approaches have been engineered to solve specific problems and later on been revealed as being equivalent to concepts found in living nature.

Control Architectures

Examples for control architectures:

- reactive control
- open-loop / closed loop control
- SMPA architectures
- Subsumption architecture
- Learning control (Neural Networks, Fuzzy, ...)
- Blackboard architectures
- Hierarchical control
- ... ... and many more ...

Reactive Control

Reactive control can be defined as a direct mapping from a ~~perceptual space~~ to a command space.

Reactive Control

Reactive control can be defined as a direct mapping from a **sensory space** to a command space.

Reactive Control

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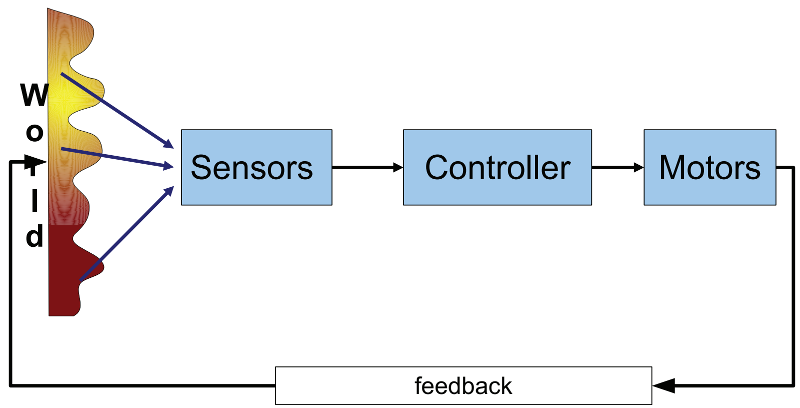

Reactive Control

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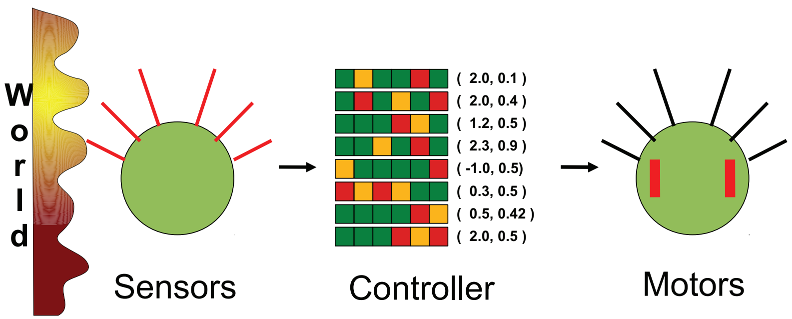


Proactive Control

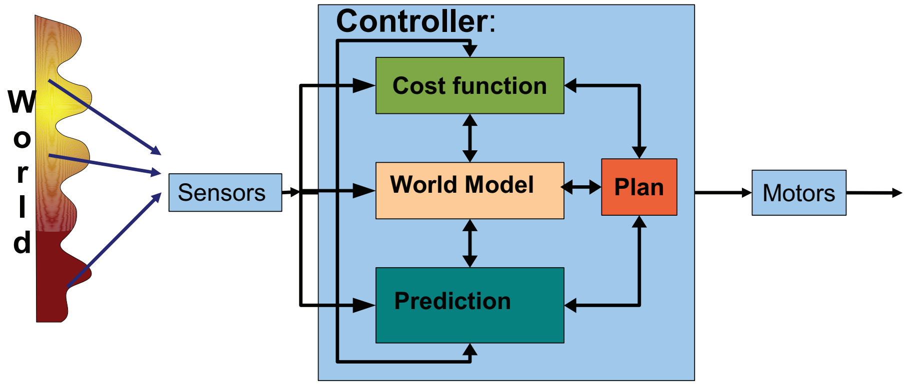
In contrast to a reactive control scheme, the proactive control uses an internal model of the world to determine and generate the next actions to perform.

Typically a proactive controller will require one or more of the following aspects:

- Internal world model
- Plan
- Prediction

Proactive Control

For proactive control, the controller has a more complicated mapping from sensory space to commands.



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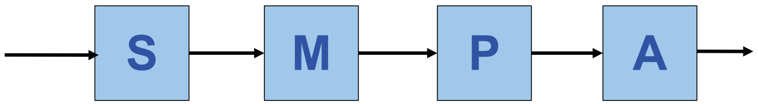
SMPA Architecture

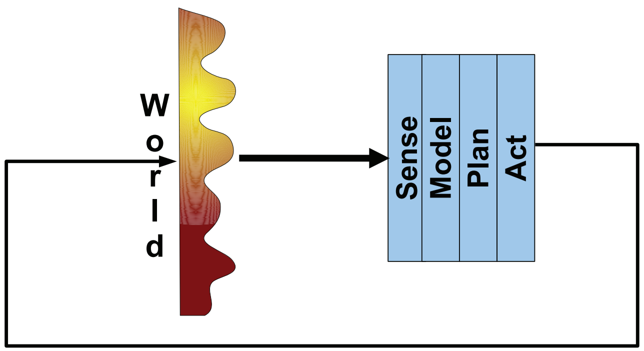
One of the most implemented control principles is the SMPA Architecture.
Here, the control task is subdivided into four blocks, that are processed as a sequence.

Sense – **M**odel – **P**lan – **A**ct



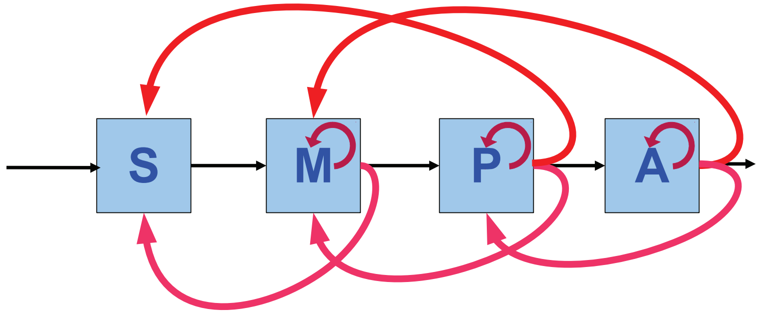
SMPA Architecture

The sensory input (Sense) obtained from the outer world is processed by the SMPA architecture onto commands controlling the robot/or the environment (Act).



SMPA Architecture

Although the SMPA architecture is organized as four modules in a row, there can be various feedback loops within these boxes, and even between these boxes.



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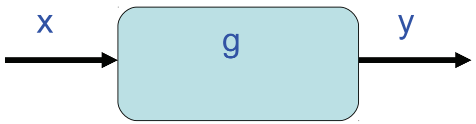
Systems Theory (engineering perspective)

The basis for classical control theory is the systems view.

Systems theory organizes the world into functional blocks that are interconnected.
The functional blocks represent dynamical systems.



The input to the system is typically denoted: x

The output from the system is denoted with: y

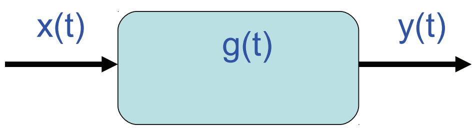
The transfer function is typically denoted: g

Systems Theory (engineering perspective)

The input x, the output y, and the transfer function g of the system are typically time dependent functions.

x(t), y(t), g(t)

e.g.: $x(t) = x_0 + A*\sin(\omega*t + \phi)$



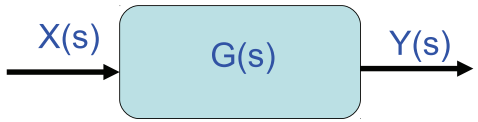
The properties g(t) of such a system can now be described by means of differential equations or by convolutions.

Calculation with convolutions (Faltung) can be complicated.

Systems Theory (engineering perspective)

Transposing the complete system x(t), y(t), g(t) from time domain into frequency domain using the Fourier transform or the more powerful Laplace transform yields:

In time domain:	x(t), y(t), g(t)	
In frequency domain:	X(iω), Y(iω), G(iω)	(Fourier)
	X(s), Y(s), G(s)	(Laplace)



Systems Theory (engineering perspective)

A lot of calculations turn out to be simpler when performed in frequency domain, e.g.

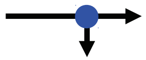
time domain:	g(t)	frequency domain	G(iω), or G(s)
differentiation	$\frac{d}{dt}$	multiplication with	*(iω) or 1*s
integration	$\int dt$	division	1/(iω) or 1/s

Systems Theory (engineering perspective)

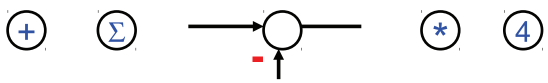
The basic elements of systems are:

- Signals, input, output: x(t), X(iω), X(s)
- System with function:

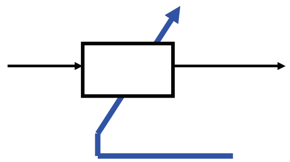
- Connections, branching:



- Arithmetic operations: sum, difference, scaling



- Modification,
  change of parameters:



Control Theory (classical control)

Control theory deals with the description and the control of dynamical systems.

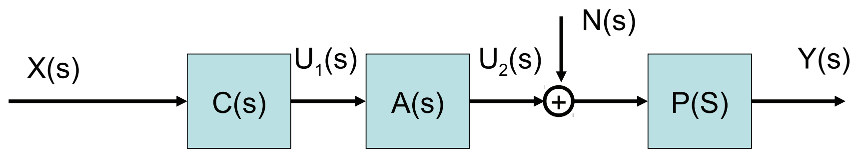
Something that is to be controlled: a system S, a plant **P**
Something that is controlling: the controller **C**
Something that is acting: an actuator **A**
Something that measures the result: sensor S, feedback **F**

The two major control modalities are:

Open loop control and closed loop control (feedback control)
[Steuerung und Regelung] (German).

Open Loop Control:

Open loop control systems consist of a chain of connected blocks: input X(s), the controller C, the actuator A, the plant P, and an output Y(s), and some (additive) noise N(s).



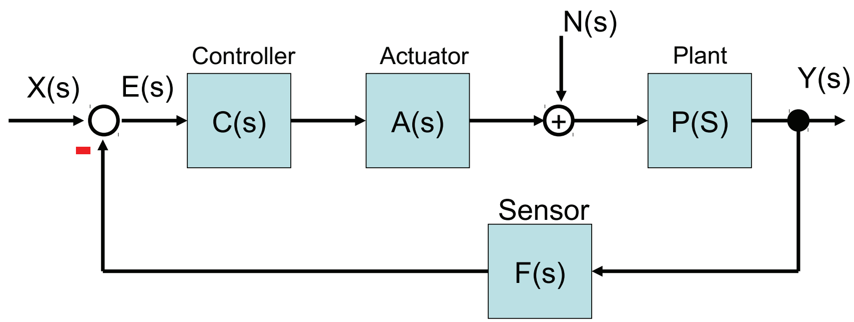
If the involved systems are linear, the output calculates easily to:

$Y(s) = P(s) * (N(s) + A(s)*C(s)*X(s))$

If actuator and noise are omitted: $Y(s) = P(s)C(s)X(s)$

Closed Loop Control

Closed loop control systems extend the open loop control by a feedback loop, with a sensor F(s) measuring the output Y(s), and a comparison of this result with the input X(s).

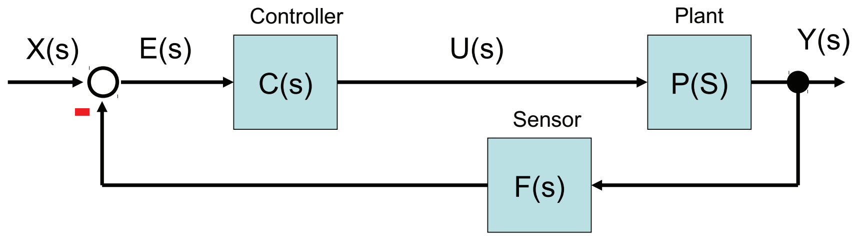


The difference between measured output Y(s) and the input X(s) (the desired value) is denoted as error E(s).

Closed Loop Control

For a reduced closed loop control (omitting noise and actuator) the closed-loop transfer function G(s) can be determined to:

$$G(s) = \frac{Y(s)}{X(s)} = \frac{output}{input}$$



$$Y(s) = \left(\frac{P(s)C(s)}{1+F(s)P(s)C(s)} \right) X(s) = G(s)X(s)$$

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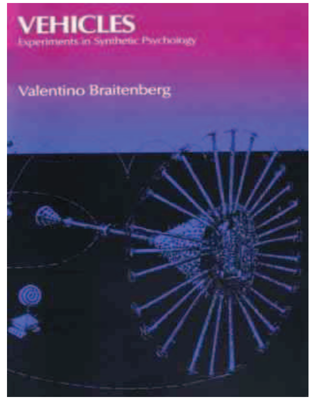
Vehicles: Valentino Braitenberg

In 1984 Valentino Braitenberg published his famous book „Vehicles: Experiments in Synthetic Psychology“

There, he proposes a set of simple vehicles that are capable of producing a variety of complex behaviors.

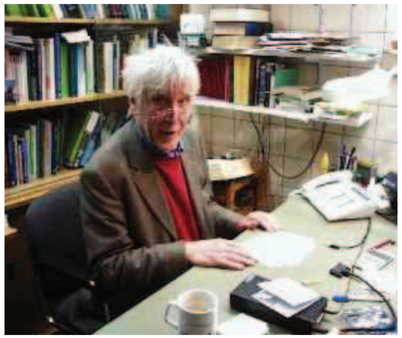
Although the internal structure of some vehicles is just a pure reactive control strategy, the behavior is complex and fascinating.



$18.23, Amazon.com, 22.5.2014

Prof. Dr. Dr. Valentino Braitenberg

Valentino Braitenberg
(Prof. Dr.med, Dr. rer.nat. h.c.)
Starting in 1968 till his retirement in 1994, Valentino Braitenberg was director of the department *Structure and Function of Natural Nerve-Net* at the Max Planck Institute for Biological Cybernetics.
He died in 2011.



His basic research interests intended to unravel the neural anatomy of the fly's visual nervous system. He concentrated on the functions of the cerebellum, examined the anatomy of the cerebral cortex and made the first computer simulations. Referring to the specificity of orientation in the visual cortex, Valentino Braitenberg also carried out psychophysical studies in humans. The vehicles he proposed were inspired by results from neuroscience and from psychology.

From: http://www.kyb.mpg.de

Braitenberg Type Vehicles

Valentino Braitenberg (Dr.med, Dr. rer.nat. h.c.) has proposed a set of vehicles that are structured in a very simple way inspired by results from neuroscience and from psychology.

The vehicles (type1, type 2, 2a,2b,2c, type 3, 3a,3b,3c, …) are designed with increasing complexity, implementing basic biological and technical control features.

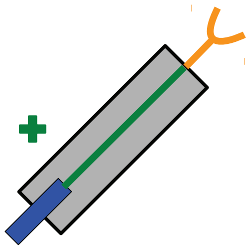
All three type of vehicles have a set of sensors, and a set of motors and pure reactive controller, with a direct, linear mapping from sensory values to motor values.

Type 1 *Braitenberg* Vehicle

The simples Braitenberg vehicle is a type 1:
„Vehicle 1 is equipped with one sensor and one motor.
The connection is a very simple one.

The more there is of the quality to which the sensor is tuned, the faster the motor goes.“

The value, the sensor is measuring from the outside is controlling the activity of the motor.
Thus, the vehicle is moving faster or slower with respect to the environment.

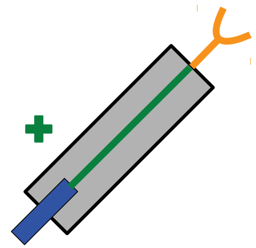


Type 1 *Braitenberg* Vehicle

Lets suppose the sensor is delivering a value which is proportional to the temperature (measured in Kelvin).

Since the connection between sensor and motor is linear, and positive (+) and the sensor gives only positive values, the vehicle is always moving forward.

In warm areas the vehicle will speed up, in cold areas the vehicle will slow down.

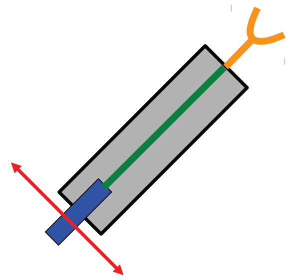


Type 1 *Braitenberg* Vehicle

Only moving straight ahead, forward (even with changing speed) is a little bit boring.

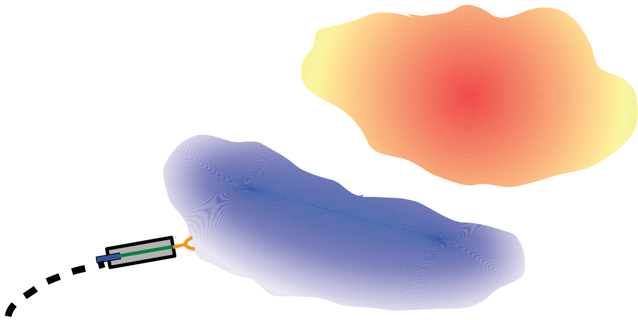
In reality, there will always exist small perturbations from the mechanical construction, the surface or from friction that will cause the vehicle to change it's direction slightly.

It is the stochastic component that makes the behavior interesting.



Type 1 *Braitenberg* Vehicle

In warm areas the vehicle will speed up,
in cold areas the vehicle will slow down,
and thus stay longer in cold regions.



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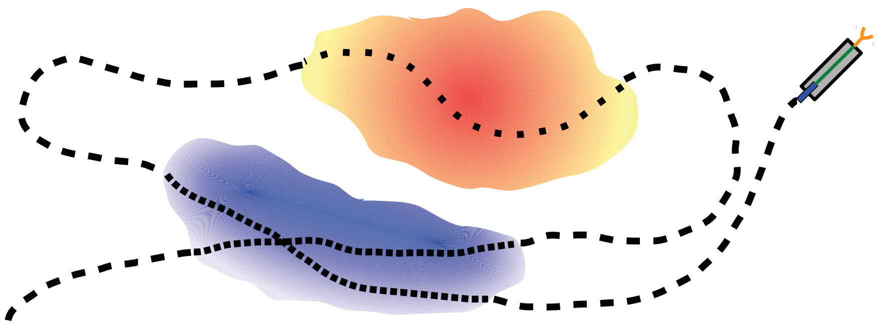
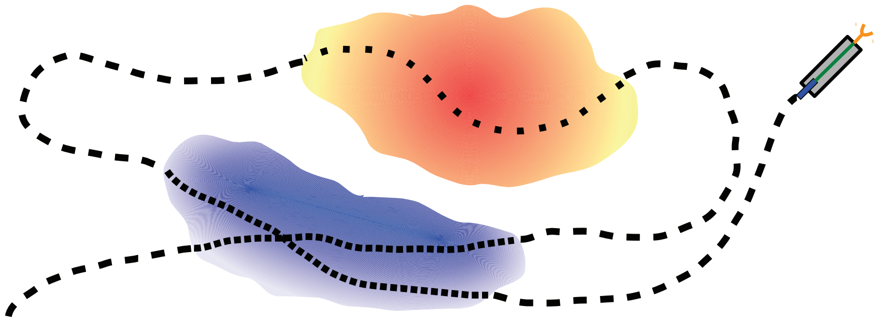


Type 1 *Braitenberg* Vehicle

In warm areas the vehicle will speed up,
in cold areas the vehicle will slow down,
and thus stay longer in cold regions.

From an „***outside perspective***“ it seems as if the vehicle „***loves***“ cold regions, and „***dislikes***“ warm regions.

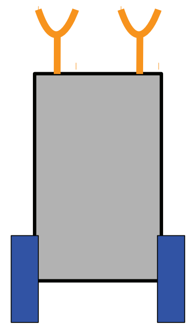


Type 2 *Braitenberg* Vehicles

The next Braitenberg vehicle is more complicated:
„Vehicle 2 is generally similar to Vehicle 1
except that it has two sensors, one on each side,
and two motors, right and left.“

„You may think of it as being a descendant of Vehicle 1,
through some incomplete process of biological reduplication:
two of the earlier brand stuck together side by side.
Again, the more the sensors are excited (+),
the faster the motors run.“

[Vehicles,VB84, pp. 12]

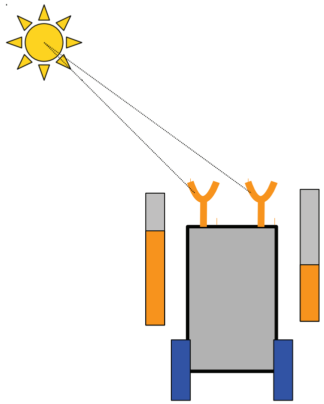


Type 2 *Braitenberg* Vehicles

Lets suppose the sensors yield a value proportional to the illumination (light dependent sensor).

Lets further assume that a light source, emitting the light from a spot is obeying the laws of physics. The light arriving at the sensors is fewer with larger distance.

In the example shown, the left sensor will receive more light than the right one.



Type 2 *Braitenberg* Vehicles

„Of course you notice right away that we can make three kinds of such vehicles, depending on whether we connect:

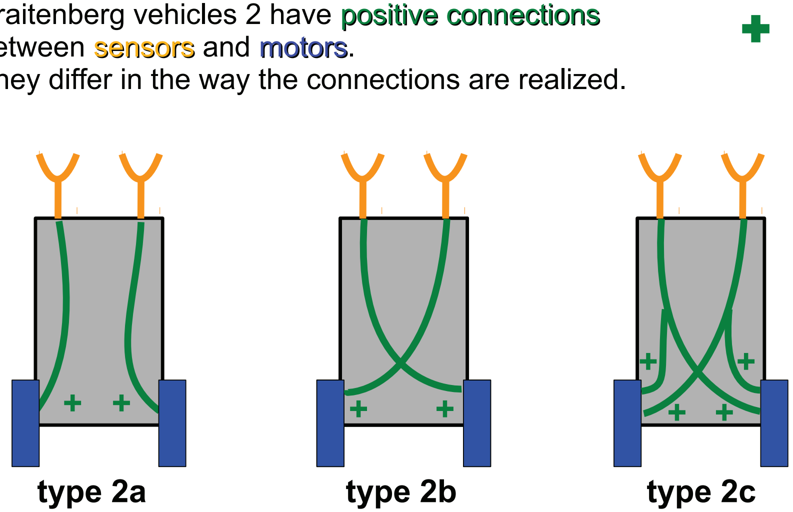
- **2a:** each sensor to the motor on the same side,
- 2b: each sensor to the motor on the opposite side, or
- **2c:** both sensors to both motors.

We can immediately dismiss case (2c), for this is nothing but a somewhat more luxurious version of Vehicle 1.
The difference between (2a) and (2b), however, is very interesting“

[Vehicles,VB84, p.6]

Type 2 *Braitenberg* Vehicles

Braitenberg vehicles 2 have positive connections between sensors and motors.
They differ in the way the connections are realized.

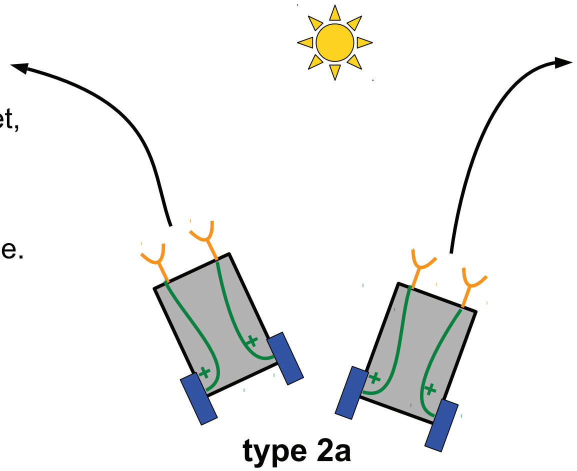


Type 2a *Braitenberg* Vehicles

Type 2a vehicles will drive away from the light source.

The further away they get, the slower they will be.

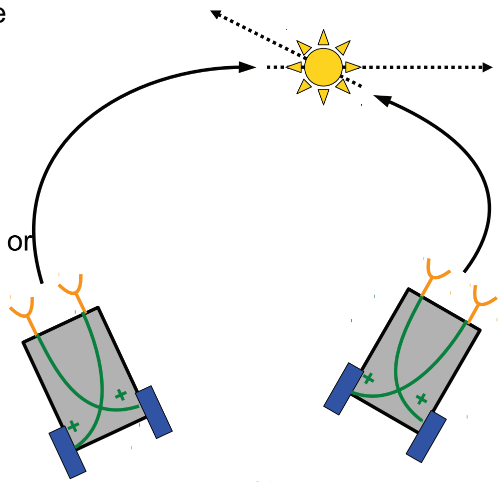
They stop if the light source is no longer visible.



Type 2b *Braitenberg* Vehicles

Type 2b vehicles will drive towards the light source almost regardless of their initial initialization with increasing velocity.

If possible, they would hit the light source, or pass by underneath.



type 2b

Type 2 *Braitenberg* Vehicles

Describing the movements of the type 2 vehicles V.Braitenberg has tried to paraphrase the observed behavior using a more human friendly vocabulary, borrowed from psychology.

The 2a vehicle is tending away from the light source
„*as if it would be afraid from light*".

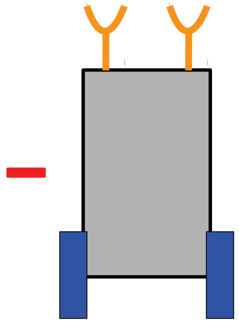
The vehicle of type 2b is moving towards the light source with increasing speed; Braitenberg calls this:
„*as if it wanted to destroy them, vehicle 2b is aggressive*".

Type 3a, 3b *Braitenberg* Vehicles

Type 3a and 3b Braitenberg have almost the same structure than the type 2Vehicles, having two sensors, and two motors, but have an altered connection type.

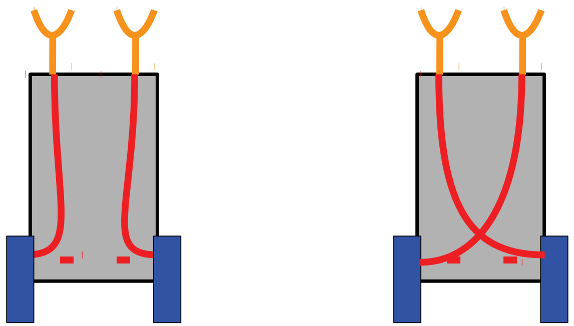
„What comes to mind is to introduce some inhibition in the **connections** between the **sensors** and the **motors**, switching the sign of the influence from positive to **negative**.
This will make the motor slow down when the corresponding sensor is activated."

[Vehicles,VB84, p.10]



Type 3 *Braitenberg* Vehicles

Braitenberg vehicles of type 3a and 3b have negative or inhibiting connections between sensors and motors.



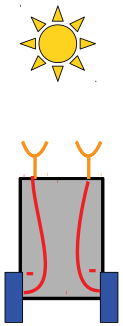
type 3a **type 3b**

Type 3a *Braitenberg* Vehicles

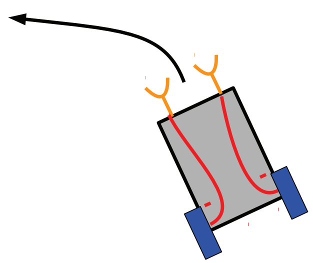
Due to the **inhibitory connections** the motors on the side facing the light source will slow down, and the vehicle will turn towards that side and thus face the light source.

The **inhibition** will make the vehicle stop in front of the light source, and will make the vehicle to face it frontal.

Type 3a vehicles end up *„sitting motionless in front of the light source“.*



type 3a

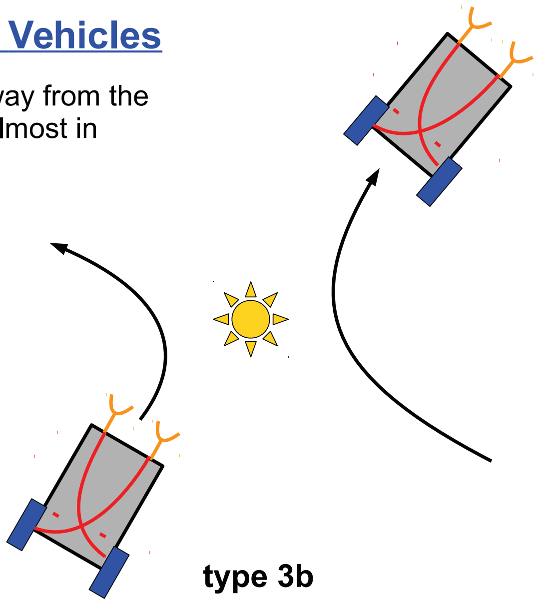


type 3a

Type 3b *Braitenberg* Vehicles

Type 3b vehicles will turn away from the light source, but they pass almost in slow-motion.

As soon as they have passed by, and are heading away from the light source, they increase their speed an may even leave the playground.



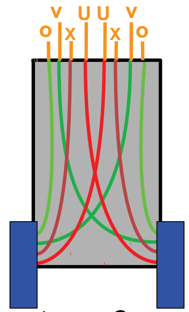
type 3b

Type 3c *Braitenberg* Vehicle

The Braitenberg type 3c vehicles have two motors and 4 pairs of sensors with both, positive and negative (or inhibitory) connections going to the same and to the opposite side.

Braitenberg proposed:
„light, temperature, oxygen concentration, and amount of organic matter; connect the first pair to the motors with uncrossed excitatory connections (**2a**) the second pair with crossed excitatory connections (**2b**), the third and the fourth pairs with inhibitory connections crossed (**3b**) and uncrossed (**3a**).“

[Vehicles,VB84, p.12]



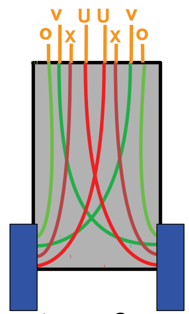
type 3c

Type 3c *Braitenberg* Vehicle

„The type **3c** vehicle dislikes high temperature, turns away from hot places, and at the same time seems to dislike light bulbs, with even greater passion, since it turns toward them and destroys them.

On the other hand it definitely seems to prefer a well-oxygenated environment and one containing many organic molecules, since it spends much of its time in such places.

But it is in the habit of moving elsewhere when the supply of either organic matter or (especially) oxygen is low.“ *[Vehicles,VB84, p.12]*



type 3c

Type 3b *Braitenberg Obstacle Avoidance*

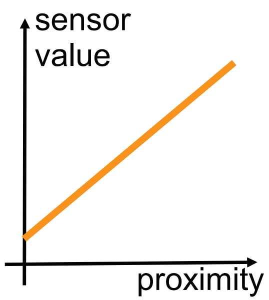
Type 3b Braitenberg vehicle is the most popular of the Braitenberg vehicles, it can be found in a lot of robotic applications.

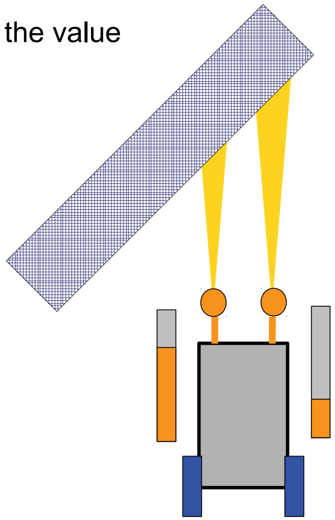
Change the sensory modality from light-sensor to a proximity measuring sensor, and you can directly implement an obstacle avoiding behavior

The closer the object is, the higher the proximity value is, the more the motor on the opposite side will be inhibited.

Type 3b *Braitenberg Obstacle Avoidance*

The closer the object is, the larger the value from the proximity sensor will be.

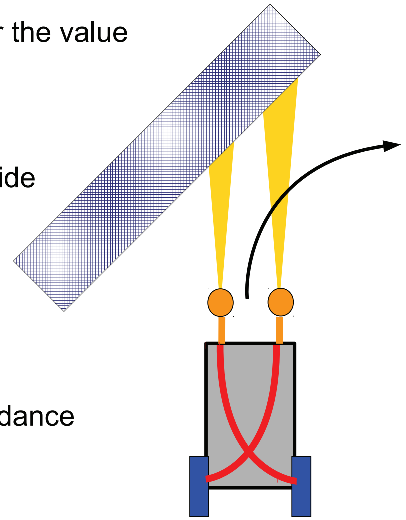




Type 3b *Braitenberg Obstacle Avoidance*

The closer the object is, the larger the value from the proximity sensor will be.

The **inhibiting connections** will make the motor on the opposite side slow down, and thus make the robot turn away from the obstacle.



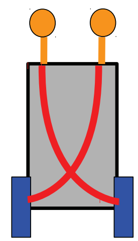
Braitenberg type 3b obstacle avoidance is very popular, caused by the *easy-to-implement* structure.

Type 3b *Braitenberg Obstacle Avoidance*

The basic principle behind Braitenberg 3b obstacle avoidance is the concept of:

antagonistic inhibition

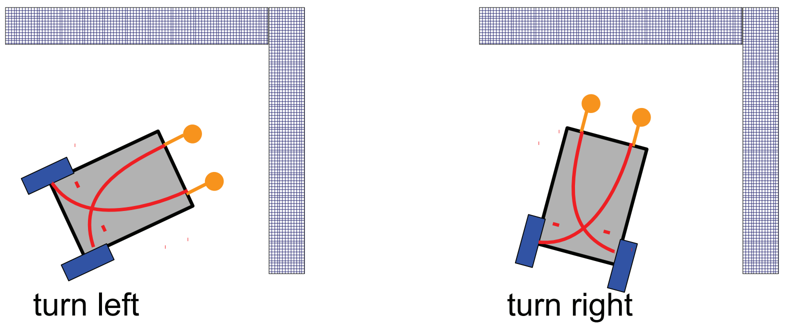
Antagonistic inhibition seems to be a fundamental principle in living nature.



Lateral inhibition was a clue to establish stable patterns (see activator-inhibitor reaction-diffusion differential equations).

Type 3b *Braitenberg Obstacle Avoidance*

Although Braitenberg 3b obstacle avoidance is fascinating powerful compared to it's complexity it is not „*fool-proof*“. Corners are already a challenge for this kind of reactive control.



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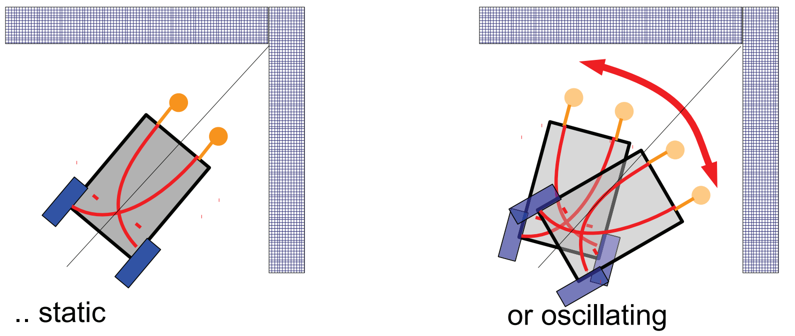
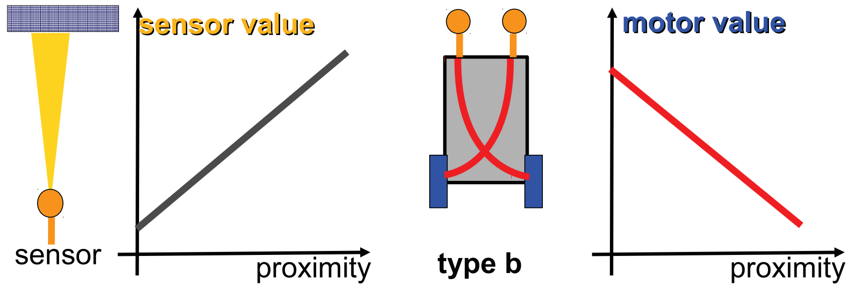


Type 1,2,3 *Braitenberg* Vehicles

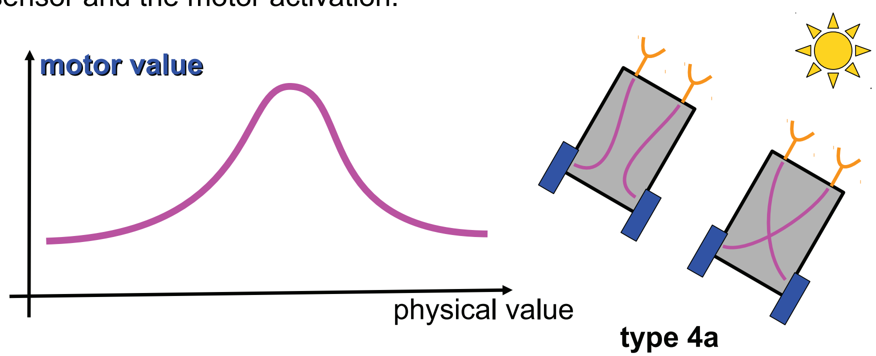
Type 1,2, and 3 Braitenberg Vehicles have a linear increasing or decreasing characteristics between physical modality (distance, proximity, light, ...) and motor values
e.g. the closer the object is, the slower the motor will run.



Type 4 *Braitenberg* Vehicles

Type 4a vehicles have a more sophisticated characteristic to map the physical modalities onto motor values,
direct connections and crossed connections are included.

Consider a non-monotonic, smooth characteristic between a (light) sensor and the motor activation.



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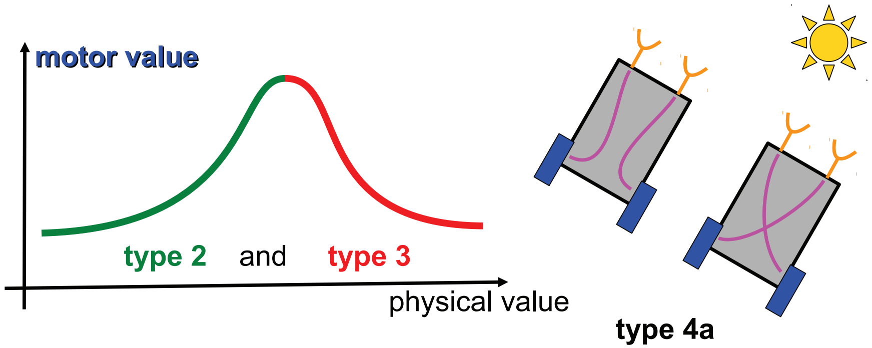
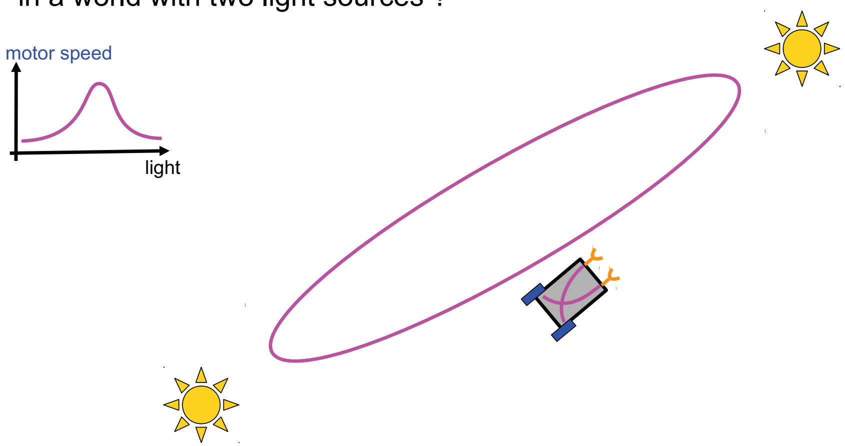


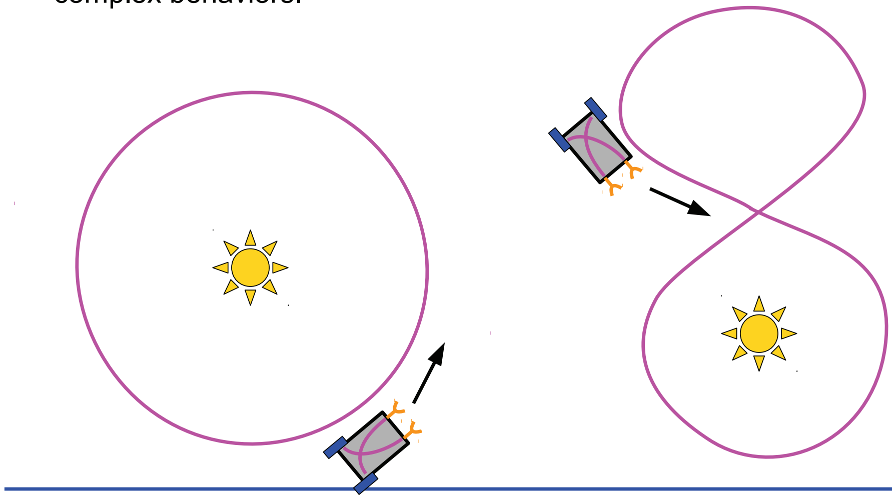
Type 4 *Braitenberg* Vehicles

How will the behavior of such a type 4a vehicle with light sensors be,
in a world with two light sources ?



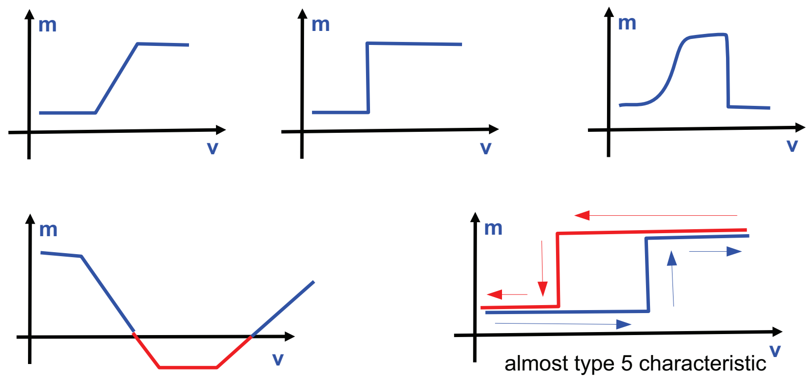
Type 4 *Braitenberg* Vehicles

Type 4a Braitenberg vehicles show a wide variety of different, complex behaviors.



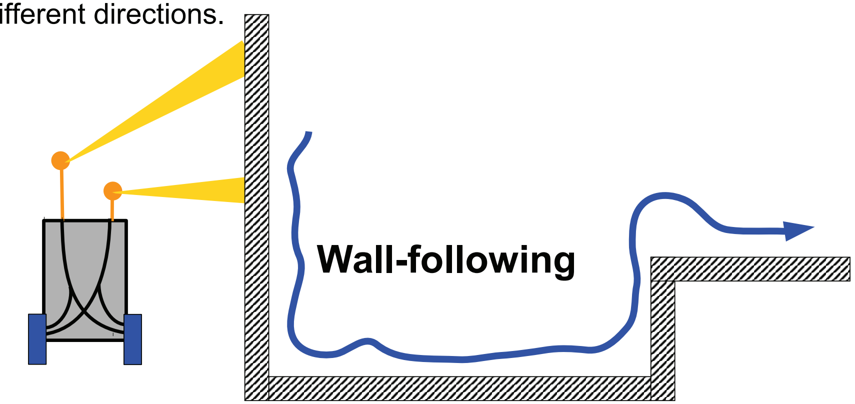
Type 4 *Braitenberg* Vehicles

Type 4b vehicles have abrupt changes in mapping the physical modalities onto motor values.



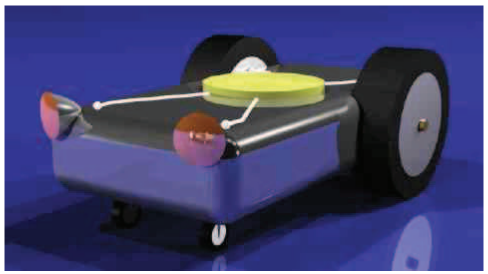
Braitenberg Vehicles

Even more sophisticated tasks like wall following can be easily implemented using the principles proposed by Valentino Braitenberg, e.g. when the sensors are allowed to scan into different directions.



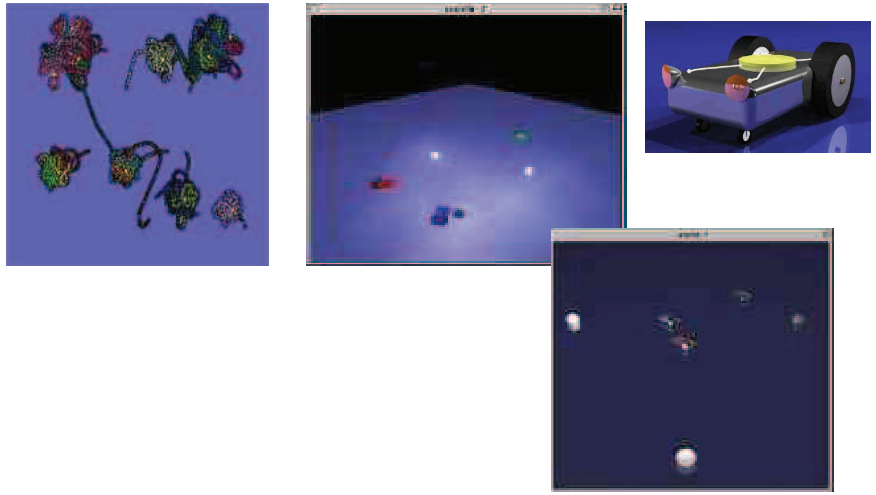
Braitenberg Vehicles, Implementations

Since the publication of Valentino Braitenberg's book,
a lot of researchers have implemented them in simulation and in hardware.
Since the principle is so easy, it is a widely used testbed for experiments and research.



From: http://people.cs.uchicago.edu/~wiseman/vehicles/

Braitenberg Vehicles, Implementations



From: http://people.cs.uchicago.edu/~wiseman/vehicles/

More Braitenberg Vehicles

- Type 1, 2, 3, 4:
  reactive control
- Type 5:
  internal states, with chains of logic elements.
- Type 6:
  design of type 5 structure by evolutionary process.
- Type 7:
  learning internal structure (Mnemotrix).
- Type 8:
  visual system
- Type 9, 10, 11, 12, 13, 14,

More Braitenberg Vehicles (according to book)

- Vehicle 1: Getting Around
- Vehicle 2: Fear and Aggression
- Vehicle 3: Love
- Vehicle 4: Values and Special Tastes
- Vehicle 5: Logic
- Vehicle 6: Selection, the Impersonal Engineer
- Vehicle 7: Concepts
- Vehicle 8: Space, Things, and Movements
- Vehicle 9: Shapes
- Vehicle 10: Getting Ideas
- Vehicle 11: Rules and Regularities
- Vehicle 12: Trains of Thought
- Vehicle 13: Foresight
- Vehicle 14: Egotism and Optimism

Roots of Complex Behavior

- Ideas from biology and from engineering
- Control architectures
- Reactive control
- Proactive control
- SMPA architecture
- Some systems theory
- Braitenberg vehicles
  - Type 1
  - Type 2
  - Type 3
  - Type 3b based obstacle avoidance
  - Type 4
  - Type 5 - 14

Some important dates:

The last lecture on **Monday July 13**,
is explicitly dedicated for **questions and answers**.
Please be prepared for this.

Written examination, is scheduled for:
Thursday, **30. July 2015** from **10:00** to 11:40,
LBH Building, Lecture Hall: III.03a

Re-Sit examination, will be:
Tuesday, **8. Sept 2015** from **10:00** to 11:40,
LBH Building

Artificial Life
Summer 2015

Roots of Complex Behavior
&
Braitenberg Vehicles

Thank you for listening

Dr. Nils Goerke, Autonomous Intelligent Systems,
Department of Computer Science, University of Bonn