Aston University

iqr simulator for large scale neural systems

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Agenda

Topic	Type
Background and introduction to iqr	Lecture
Getting started with iqr	Tutorial
Modules and interfaces	Lecture
Interfacing a camera	Tutorial
Developer	Lecture

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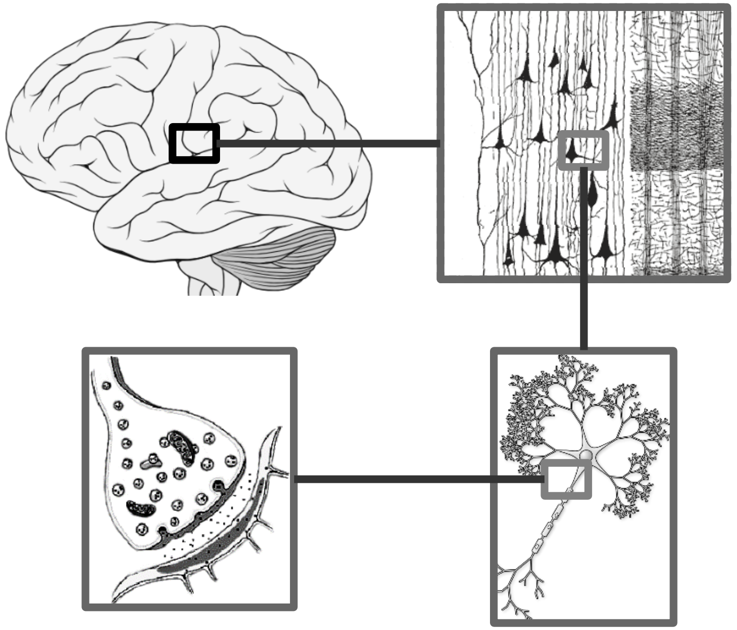
Background and introduction to iqr

Understanding the brain

- The brain is an extraordinarily complex machine
- Workings can be described at a multitude of levels of abstractions (Sub-cellular…Areas)
- Different levels not mutually exclusive
  - Need to combine into a multi-level description
  - Only a holistic, systemic view can adequately explain the system under investigation



Bernardet, U., & Verschure, P. F. M. J. (2010). iqr: A Tool for the Construction of Multi-level Simulations of Brain and Behaviour. Neuroinformatics, 8(2), 113–34.

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The synthetic approach

- Understanding systems through building them
- Process of building as such yields insights;
  - Explicitly state the target function of the system
  - Assign meaning to all elements and relations between elements of the system
- Building functioning systems, rather than detached models
  - Span from sensory processing to the behavioral output
- Synthetic systems are open to unlimited measurement and manipulation

Verschure, P. F. M. J., & Althaus, P. (2003). A real-world rational agent: unifying old and new AI. Cognitive Science, 27(4), 561–590.

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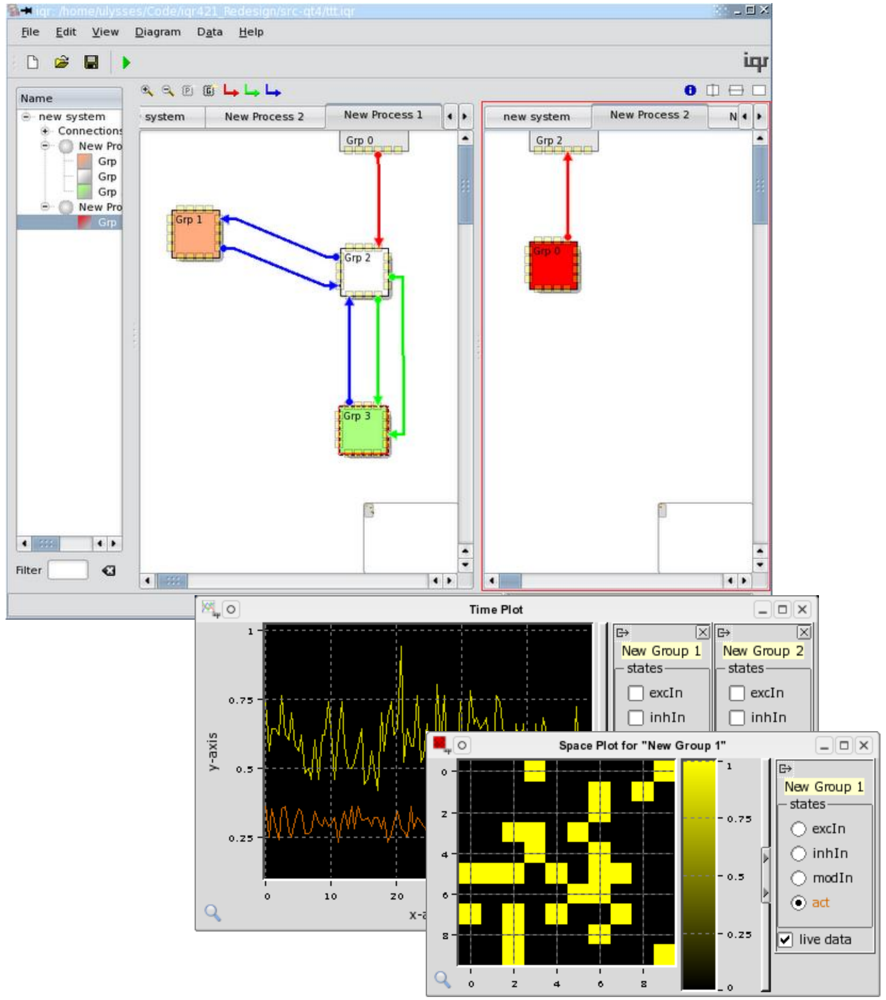
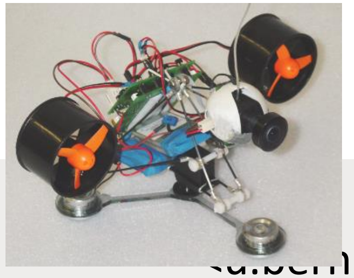
The large-scale neuronal system simulator iqr

- Tool to support the synthetic approach
  - Real-world devices
  - Support for large-scale models
- Features
  - Graphical user interface for designing
  - On-line visualization and analysis of data
- Pre-defined neuron and synapse types
- Open architecture for new neurons, synapses, and hardware interfaces
- Open source: http://iqr.sourceforge.net





System architecture

- System: Top-level unit
- Processes: Organizational units → no computational functions
- Group: Specific aggregation of neurons of identical type
- Connection:
  - Feed information from group to group
  - Aggregation of synapses of identical type
  - Definition of the arrangement of the synapses
- Connection framework:
  - Deals with axon, synapse, and dendrite of the neurons
  - Computational element: Synapse

- ➔ System [==1]
  - ➔ Process [>=1]
    - ➔ Group [>=1]
      - ➔ Neuron Type
    - ➔ Module [==0|1]
  - ➔ Connection [>=0]
    - ➔ Synapse Type

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Neurons in iqr

- Neurons are the core computational units in brain-like information processing system
- Different “Standard Types” provided by iqr
- iqr provides a simple framework for defining your own types of neurons
- No difference between user-defined neurons and “standard” types

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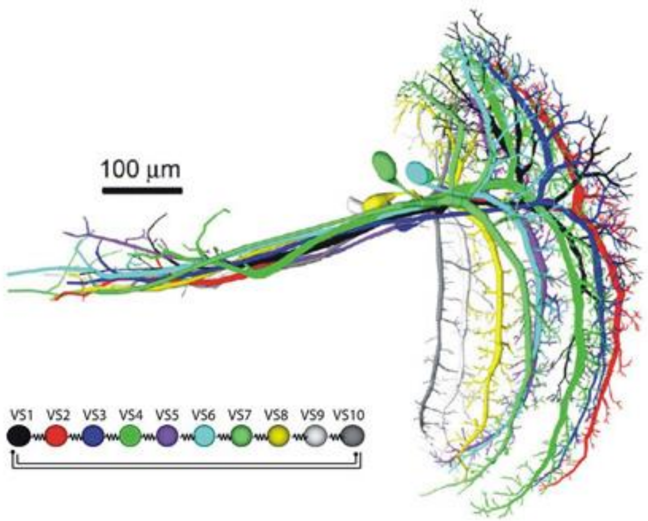
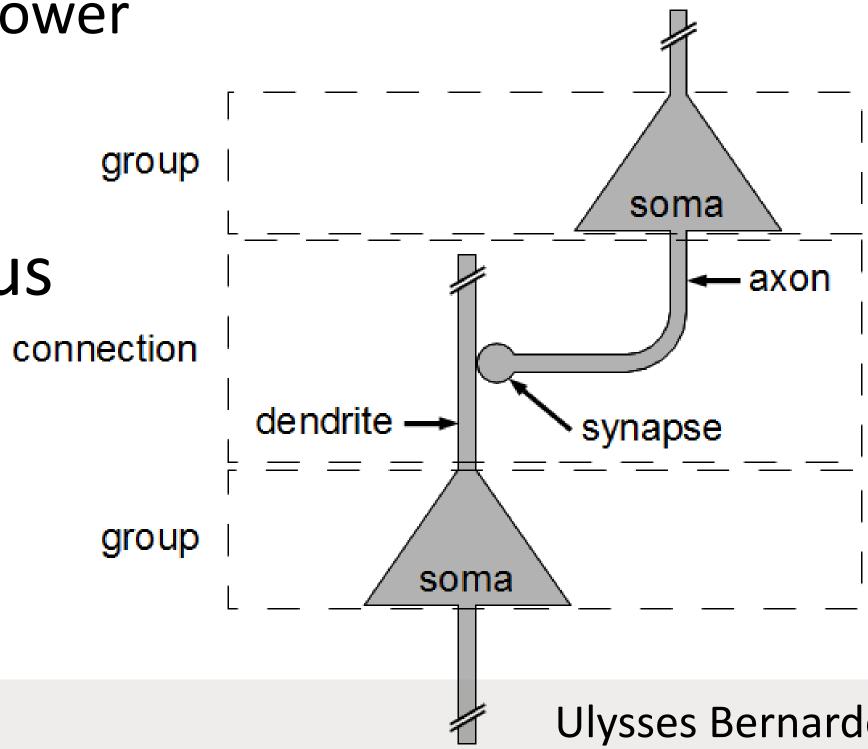
Information exchange: Connection



- A human brain consists of ~85 billion neurons
- Neurons outnumbered by synapses
  - Synapses per average neuron: 1,000 - 10,00
- Ratio of number of neurons vs. number of synapses
  - Biological neuronal networks draw their computational power from the large-scale integration of information in the connectivity between neurons
- Large scale neuronal models require heterogeneous connectivity patterns
- Providing a flexible, yet easy to use way to define connectivity is a cornerstone of iqr



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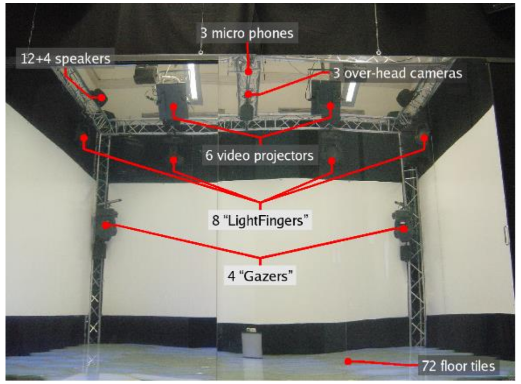
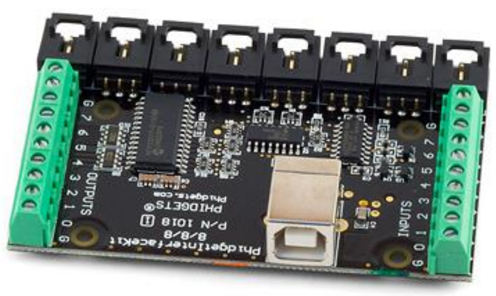
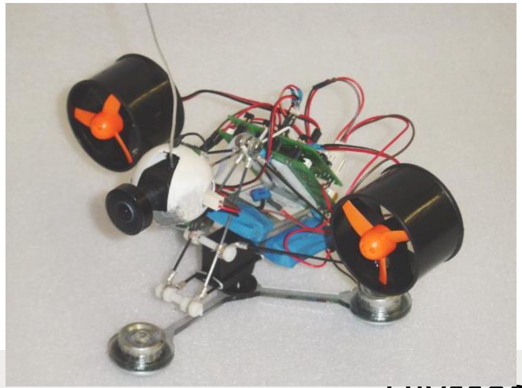
Modules: Interfaces to real-world devices

- Cameras
- Audio
- Pan-tilt system
- Robots
  - K-team robots
  - E-puck
  - Blimps
  - Strider
  - iCub (via YARP)
  - .....







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iqr facts

- Open Source (Gnu Public License)
  hosted on SourceForge http://sourceforge.net/projects/iqr
  - Repository of iqr packages
  - Documentation
  - Bug reports
  - Feature request
  - Browse and check out the source code of iqr
- 60’512 lines of C++ code
  (development effort estimate in Person-Months: 190.66, estimated cost to develop: 2’146’350$ (generated using David A. Wheeler’s “SLOCCount”))
- Qt widget set
- Multi-threaded
- XML system description

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Simulations in iqr

- Computation
  - Spiking / rate coding
  - Compartmental / abstract
  - Discrete vs continuous simulation

- Architecture
  - Feedforward / feedback
  - Learning / non-learning

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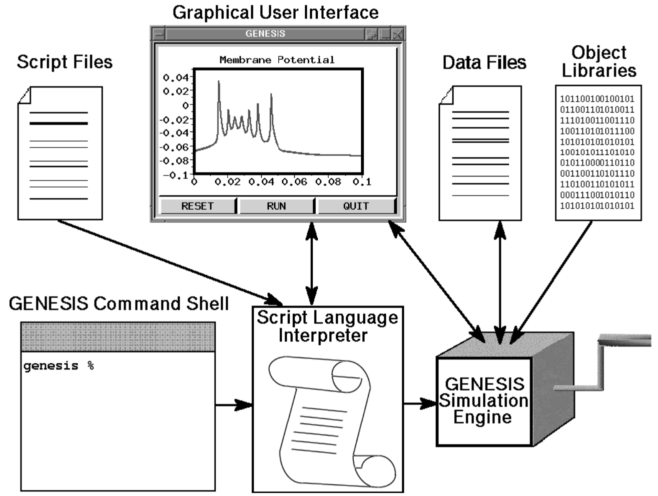
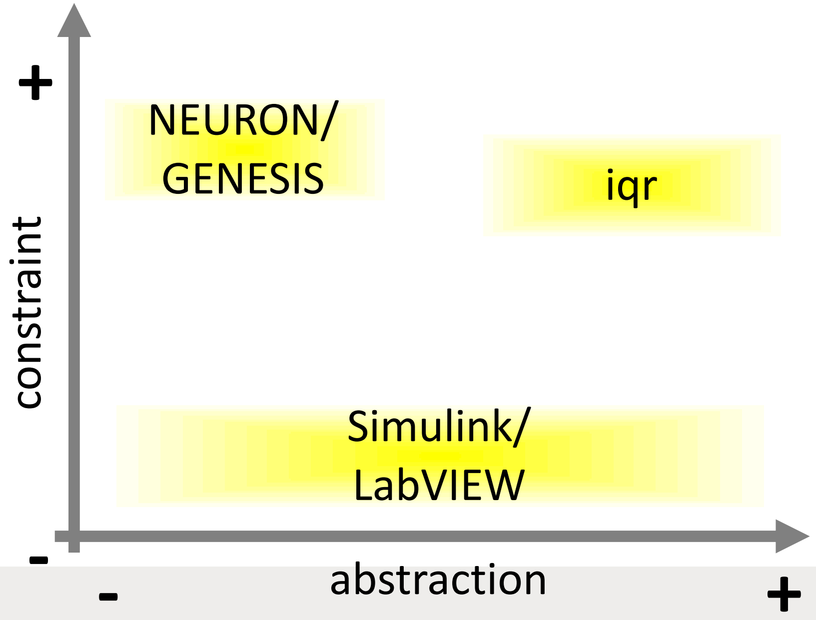
Simulators



- GENESIS
  Simulation environment for constructing realistic models of neurobiological systems at many levels of scale including subcellular processes, individual neurons, networks of neurons, and neuronal systems.
- NEURON
  models individual neurons via the use of sections which are subdivided into individual compartments by the program. Programs can be written interactively in a shell, or loaded from a file



- LabVIEW
  Platform and development environment for a visual programming language. Commonly used for data acquisition, instrument control, and industrial automation.
- Simulink
  Tool for modeling, simulating and analyzing multidomain dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries.

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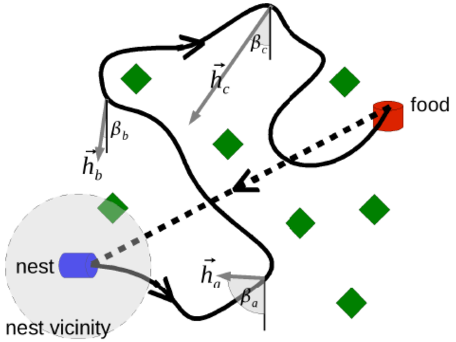
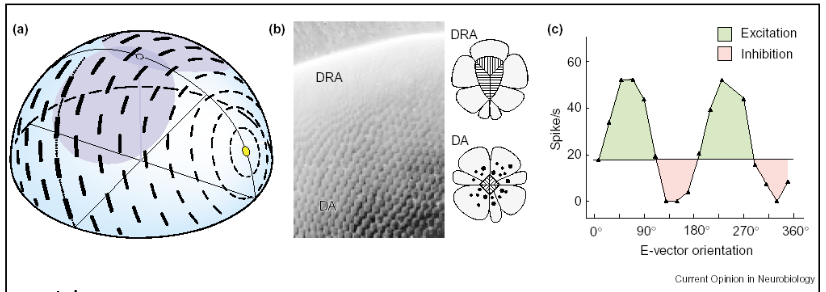
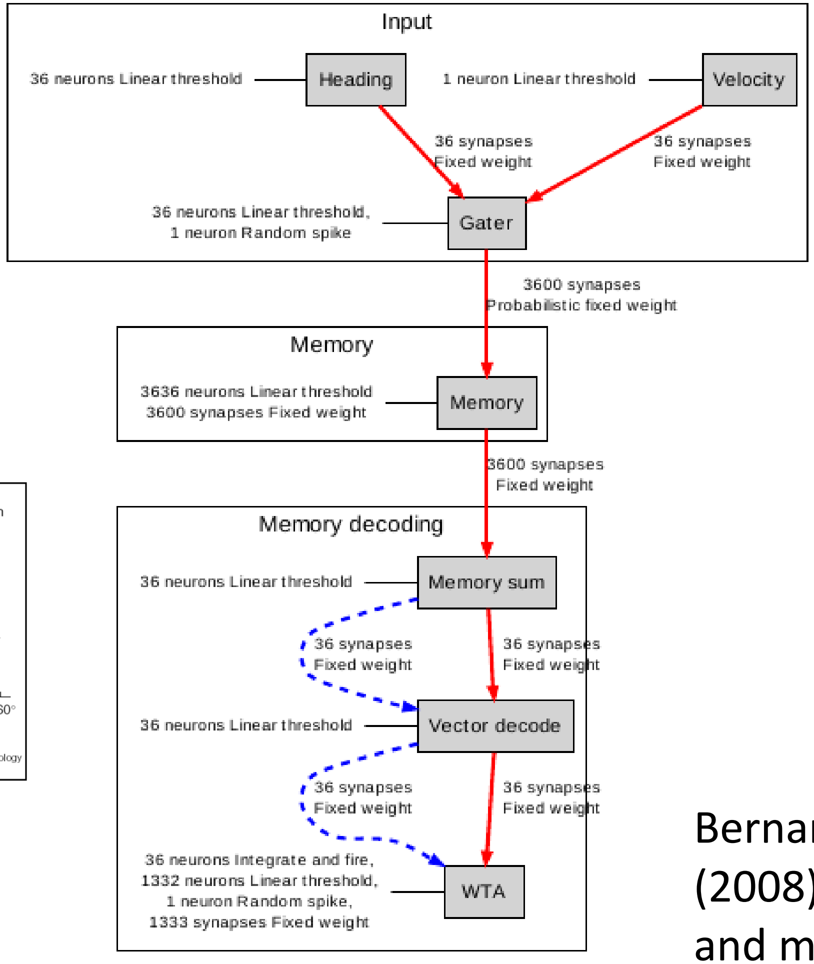
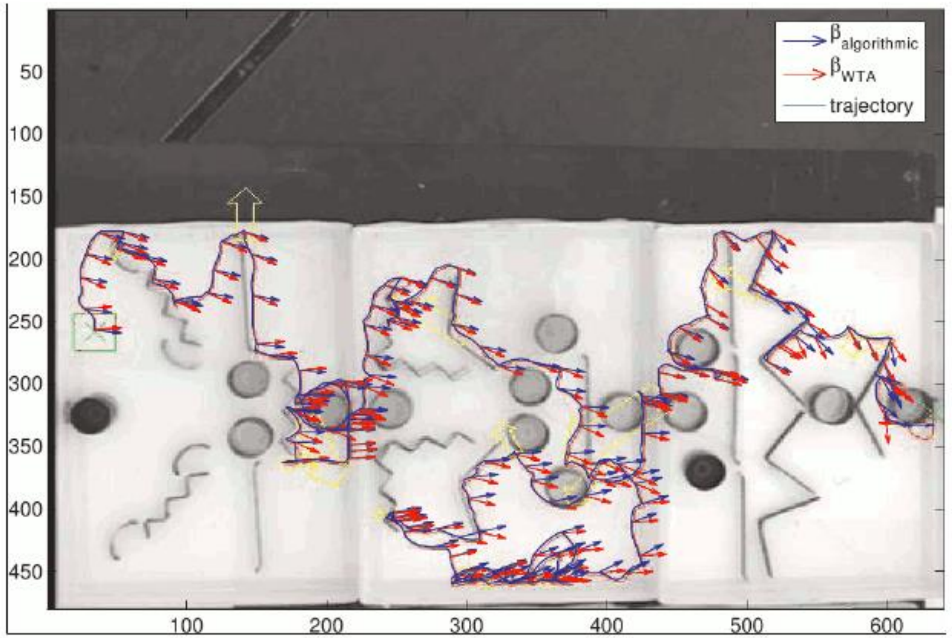
Example: Path integration and orientation in insects





cricket





Bernardet, U., Bermúdez I Badia, S., & Verschure, P. F. M. J. (2008). A model for the neuronal substrate of dead reckoning and memory in arthropods: a comparative computational and behavioral study. Theory in biosciences, 127(2), 163-175. Springer Berlin

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Working with iQR

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Preparation

Installing iqr

- Download Linux image from https://drive.google.com/file/d/1oLYpW3gZCc13LMx94p71Ck8E9GTufTH3/view
- (Windows only): Install the binary from https://sourceforge.net/projects/iqr/files/iqr/2.5.5/

Manuals, Tutorials, example files

- Download zip file from ####

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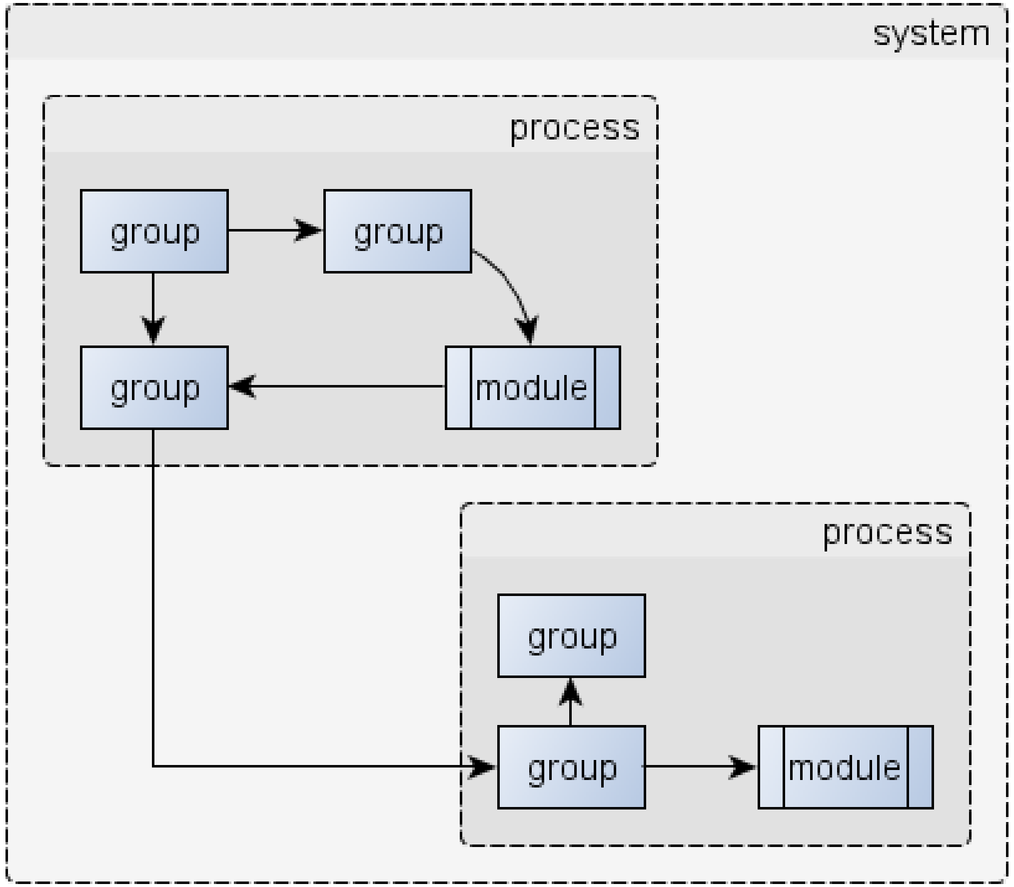
Models in iqr

- System [==1]
  - Process [>=1]
    - Group [>=1]
      - Neuron [>=1]
    - Module [==0|1]
  - Connection [>=0]
    - Synapse [>=1]



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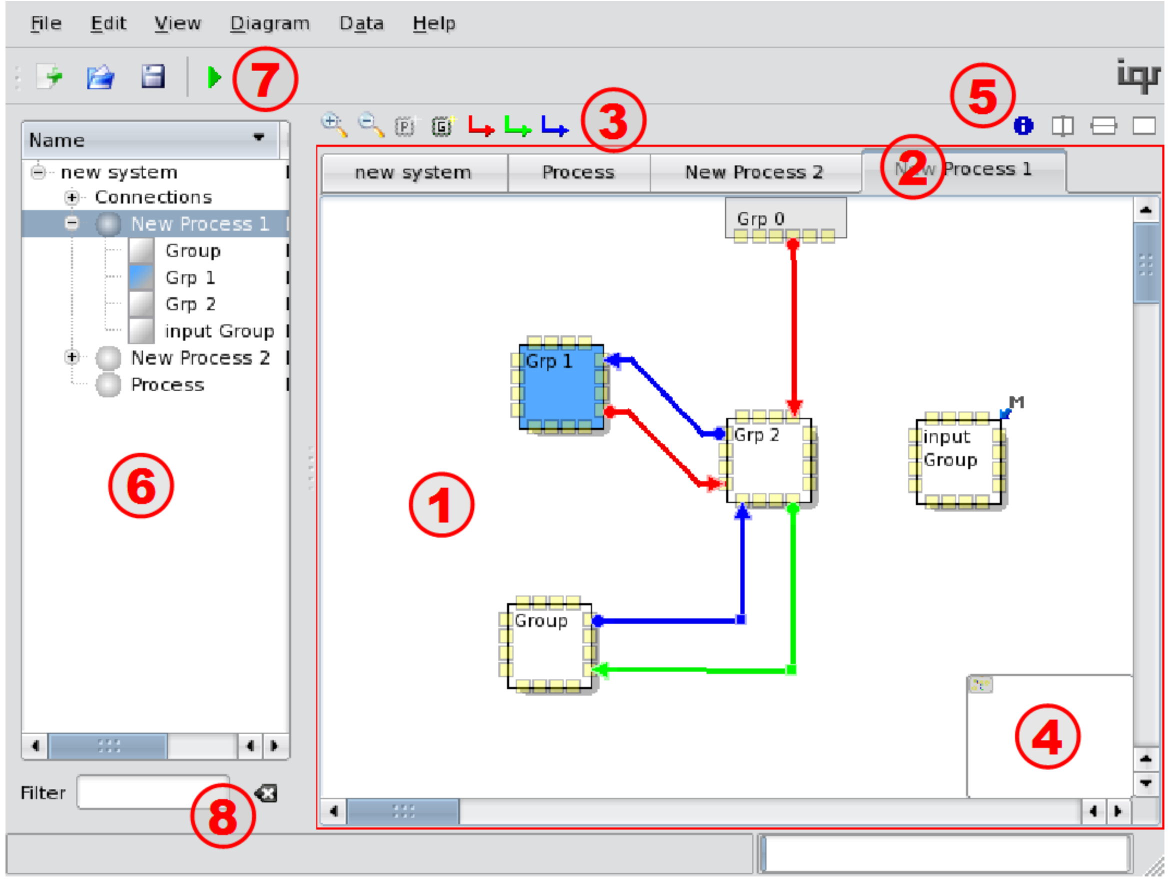
The iqr GUI

1. diagram editing pane
2. tab-bar
3. diagram toolbar
4. panner
5. splitter
6. browser
7. simulation toolbar



Split the diagram editing pane into two separate views by using the **splitter** (fig. 2.1⑤). From left to right: split vertically, horizontally, revert to single window view.

Zoom in and out of the diagram

Add a new process to the system level

Add a new group to the current process

Add a new connection between groups: excitatory (red), modulatory (green), inhibitory (blue)

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Demo

GUI INTRO

Data Visualization and Collection

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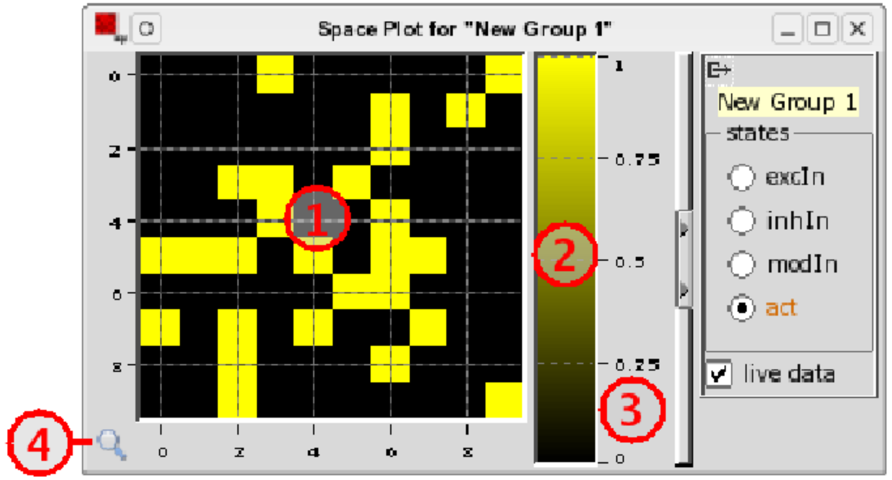
Space plots

- A Space plot as shown displays the state of each cell in a group in the plot area
- To create a new Space plot
  - right click on a group in diagram editing pane or browser
  - select Space plot from the context-menu
- The value for the selected state is color coded, the range indicated in the color bar
- A Space plot plots one state of one single group



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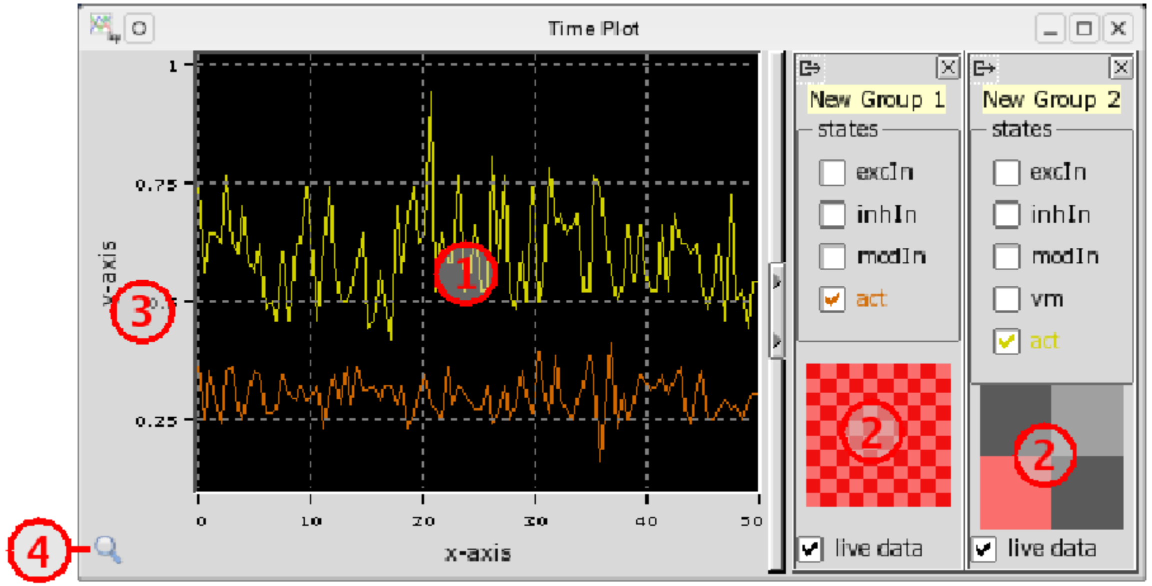
Time plots

- Plots state(s) of neurons against time
- Time plots display the average value of the states of an entire group or region of a group
- A Time plot can
  - plot several states
  - states from different groups
- Each state is plotted as separate trace
- drag & drop
  - group
  - region



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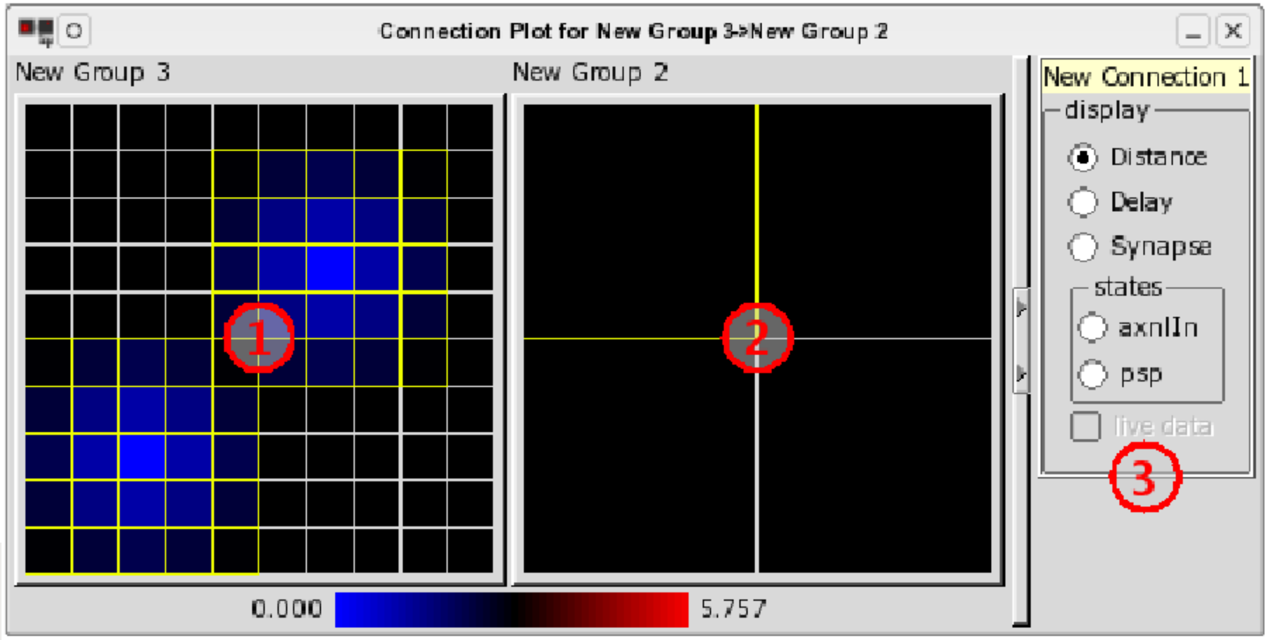
Connection plots

- Visualize the static and dynamic properties of connections and synapses.
- left: source group, right: target group
- Static properties of a connection, i.e. the Distance or Delay
- Internal states by selecting Synapse , and one of the states in the list



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Saving + loading configurations

- You can save the arrangement and the properties of the current set of plots and Data Sampler
- menu:
  - Data → Save Configuration
  - Data → Open Configuration

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→ Demo data visualization and saving

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NEURONS IN IQR

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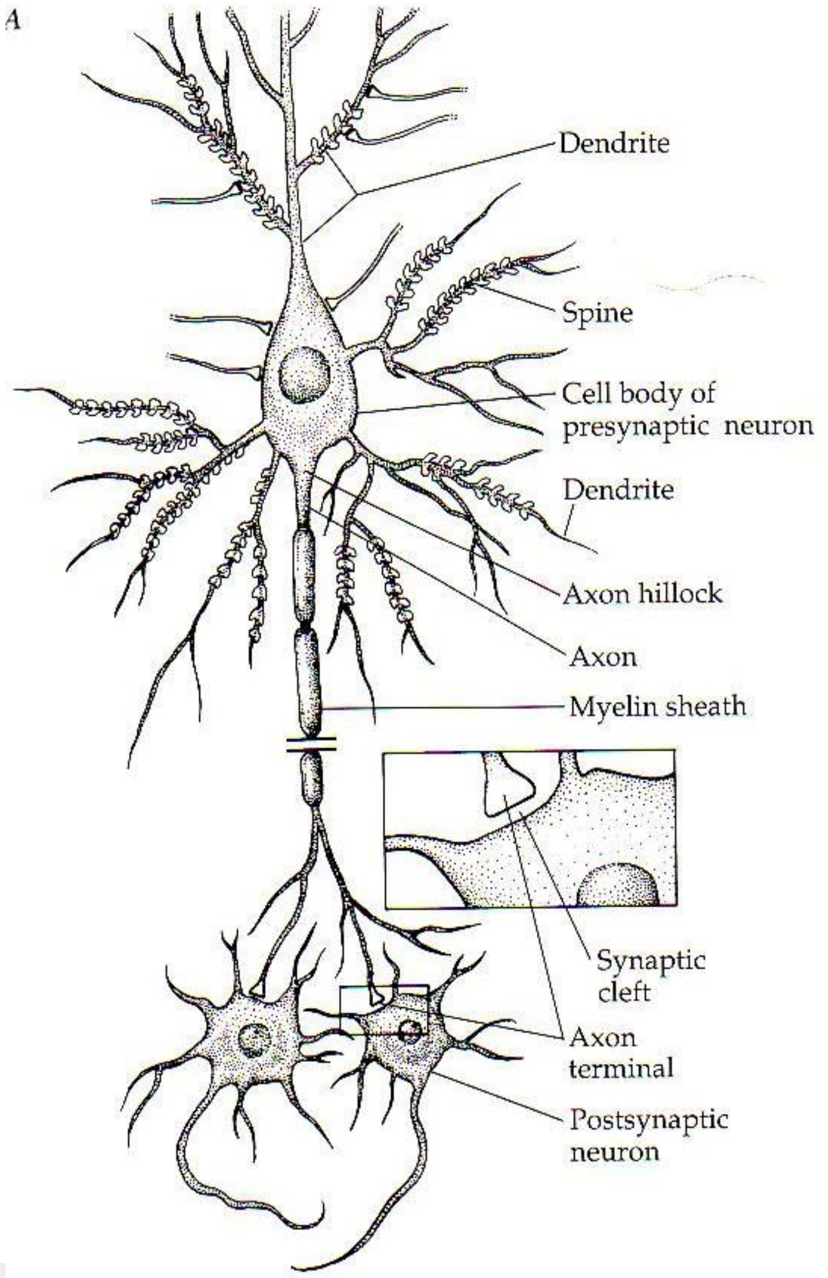
Basic morphology of neurons

- Neurons are the functional cellular unit the nervous system
- Three main parts:
  - Soma (1)
  - Dendrite (>=1)
  - Axon (==1)
- Soma and dendrites receive signals from other neurons
- Axon are transmitting signals to other neurons
- Synapse
  - Contact point between the axon of one neuron and a dendrite or soma of another
  - Can be excitatory or inhibitory



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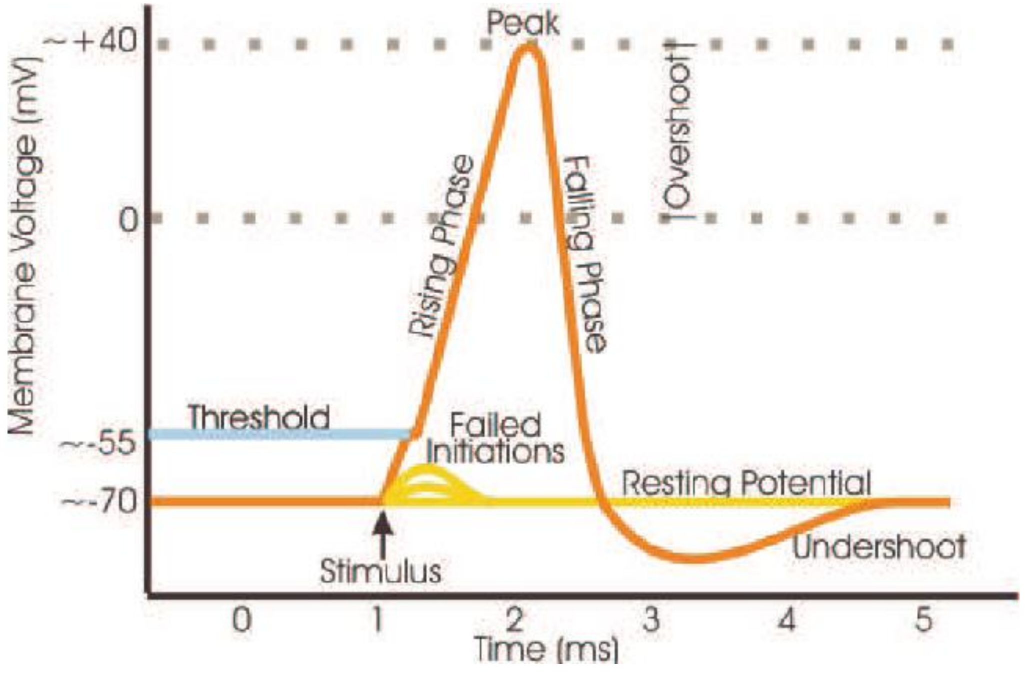
The action potential



- All neurons have a resting potential
  - -90 - -70mV
- Rapid changes of the resting potential are referred to as "action potentials"
  - Peak at ~+40mV
  - Depolarization < 1ms
  - Repolarization < 1ms
  - Refractory period of ~1-2ms
  - Speed of AP propagation: 10 – 100 m/s
- The action potential is the most common "signal" used for communication between neurons

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Neurons in iqr

- Neurons are the core computational units in brain-like information processing system
- Different “Standard Types” provided by iqr
- iqr provides a simple framework for defining your own types of neurons
- No difference between user-defined neurons and “standard” types

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Linear Threshold neurons

$$a_i(t+1) = \begin{cases} v_i(t+1) & \text{with probability } Prob \text{ for } v_i(t+1) \geq ThSet \\ 0 & \text{otherwise} \end{cases}$$

$$\begin{aligned} v_i(t+1) = VmPrs_i v_i(t) \\ + ExcGain_i \sum_{j=1}^{m} w_{ij} a_j(t - \delta_{ij}) \\ - InhGain_i \sum_{k=1}^{n} w_{ik} a_k(t - \delta_{ik}) \end{aligned}$$

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Linear Threshold neurons

Linear threshold	
Excitatory gain	Gain of excitatory inputs. The inputs are summed before being multiplied by this gain.
Inhibitory gain	Gain of inhibitory inputs. The inputs are summed before being multiplied by this gain.
Membrane persistence	Proportion of the membrane potential remaining after one time step if no input arrives
Clip potential	Limits the membrane potential to values between VmMax and VmMin.
Minimum potential	Minimum value of the membrane potential
Maximum potential	Maximum value of the membrane potential
Probability	Probability of output occurring during a single time step
Threshold potential	Membrane potential threshold for output activity

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Integrate & Fire neurons

$$a_i(t{+}1) = \begin{cases} SpikeAmpl & \text{with probability } Prob \text{ for } v_i(t+1) \geq ThSet \\ 0 & \text{otherwise} \end{cases}$$

$$\begin{aligned} v_i(t+1) = VmPrs_i v_i(t) \\ &+ ExcGain_i \sum_{j=1}^{m} w_{ij} a_j(t - \delta_{ij}) \\ &- InhGain_i \sum_{k=1}^{n} w_{ik} a_k(t - \delta_{ik}) \end{aligned}$$

After cell i produces a spike, the membrane potential is hyperpolarized such that

$$v_i'(t+1) = v_i(t+1) - VmReset$$

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Integrate & Fire neurons

Integrate & fire	
Clip potential	Limits the membrane potential to values between VmMax and VmMin.
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Membrane persistence	Proportion of the membrane potential remaining after one time step if no input arrives
Minimum potential	Minimum value of the membrane potential
Maximum potential	Maximum value of the membrane potential
Probability	Probability of output occurring during a single time step
Threshold potential	Membrane potential threshold for output of a spike
Spike amplitude	Amplitude of output spikes
Membrane potential reset	Membrane potential reduction after a spike

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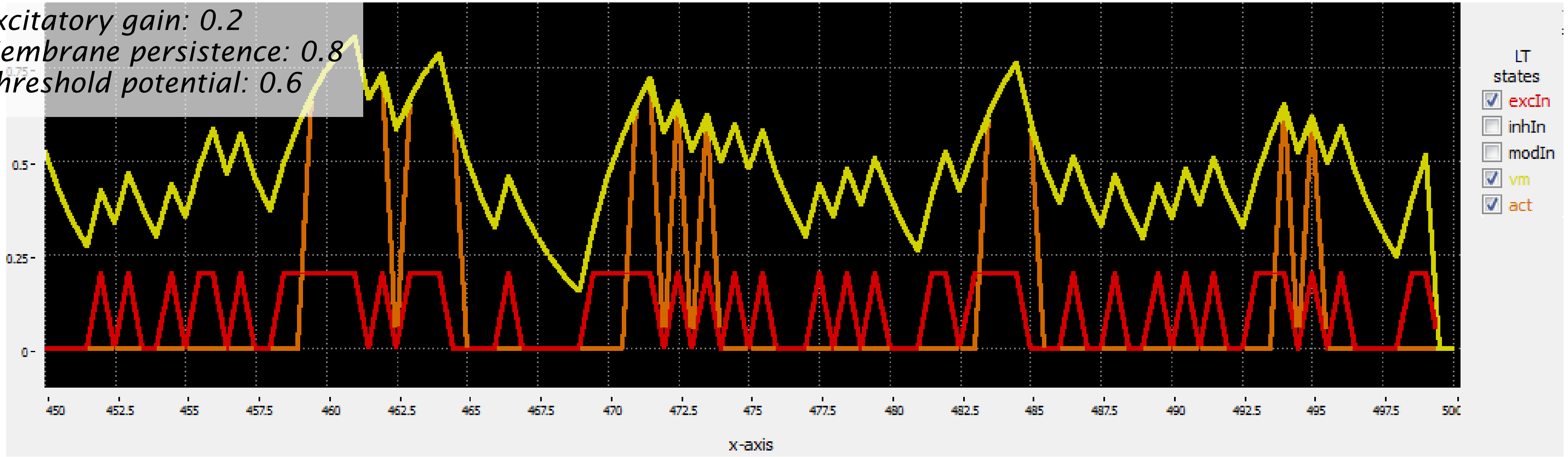
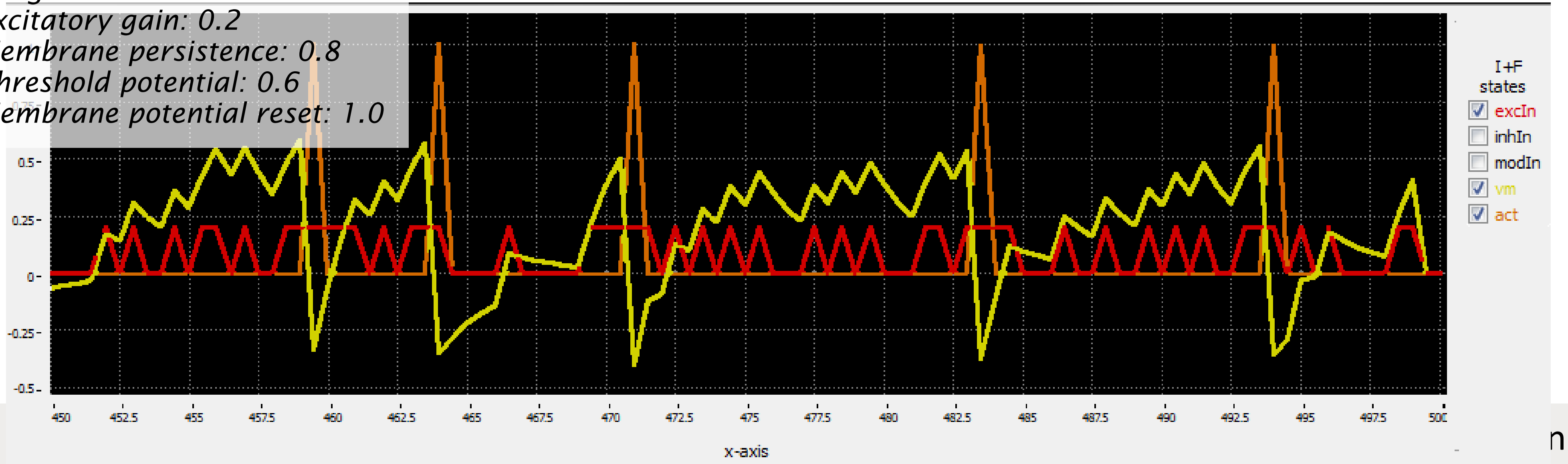
Neuron behavior

Linear Threshold
Excitatory gain: 0.2
Membrane persistence: 0.8
Threshold potential: 0.6



Integrate + Fire
Excitatory gain: 0.2
Membrane persistence: 0.8
Threshold potential: 0.6
Membrane potential reset: 1.0



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Random spike neurons

- Releases a spike per timestep with a user-defined spike probability
- Time series of the output spikes forms a Poisson process (i.e. large gaps between events are less likely to occur than short ones)
- Receives no input and has no membrane potential

Random spike	
Probability	Probability of a spike occurring during a single time step
Spike amplitude	Amplitude of each spike

$$a_i(t+1) = \begin{cases} SpikeAmpl & \text{with probability } Prob \\ 0 & \text{otherwise} \end{cases}$$

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iqr Simulator for large scale neural systems: Connectivity framework

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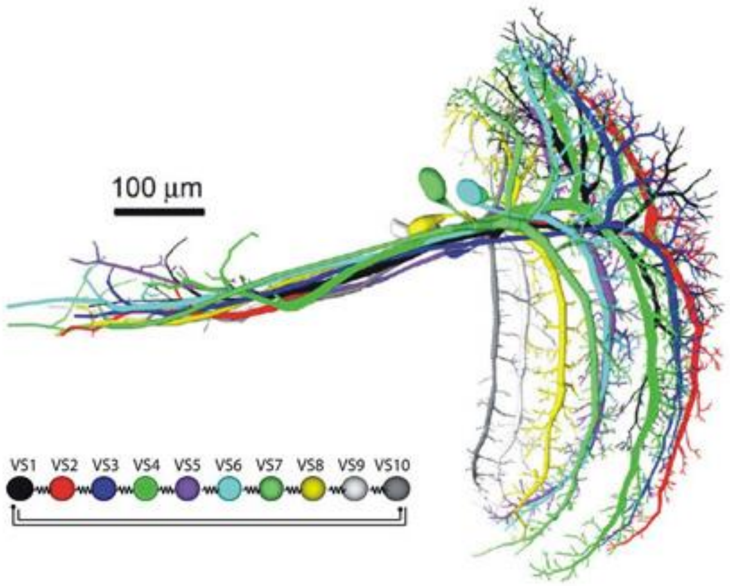
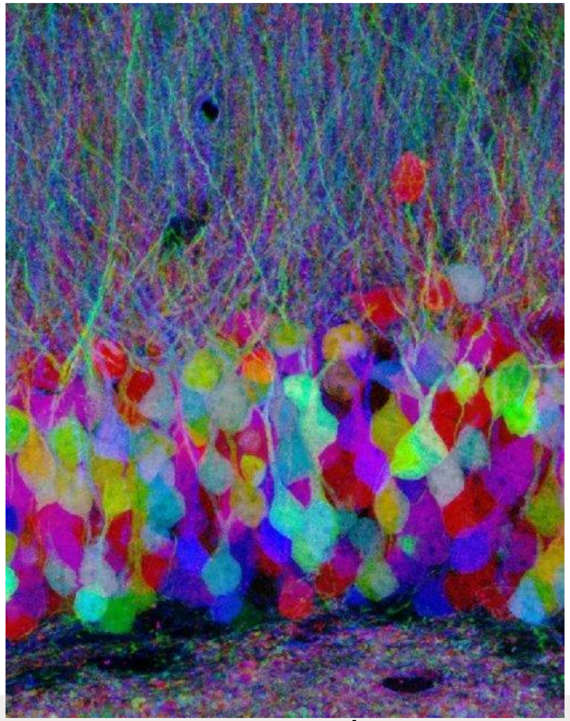
The connections challenge

- Large scale neuronal models require heterogeneous connectivity patterns
- Providing a flexible, yet easy to use way to define connectivity is a cornerstone of iqr
- The definition needs to be compact and broad
- A generic way to define connectivity can be used to describe anatomical data in general





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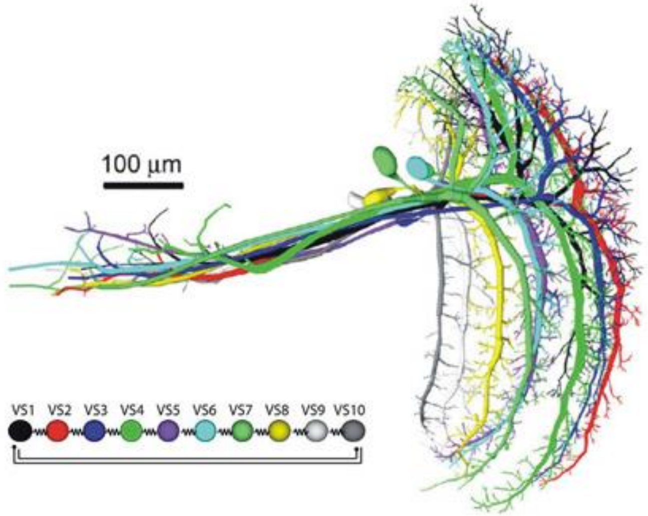
The power of connectivity



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  - Synapses per average neuron: 1,000 - 10,00
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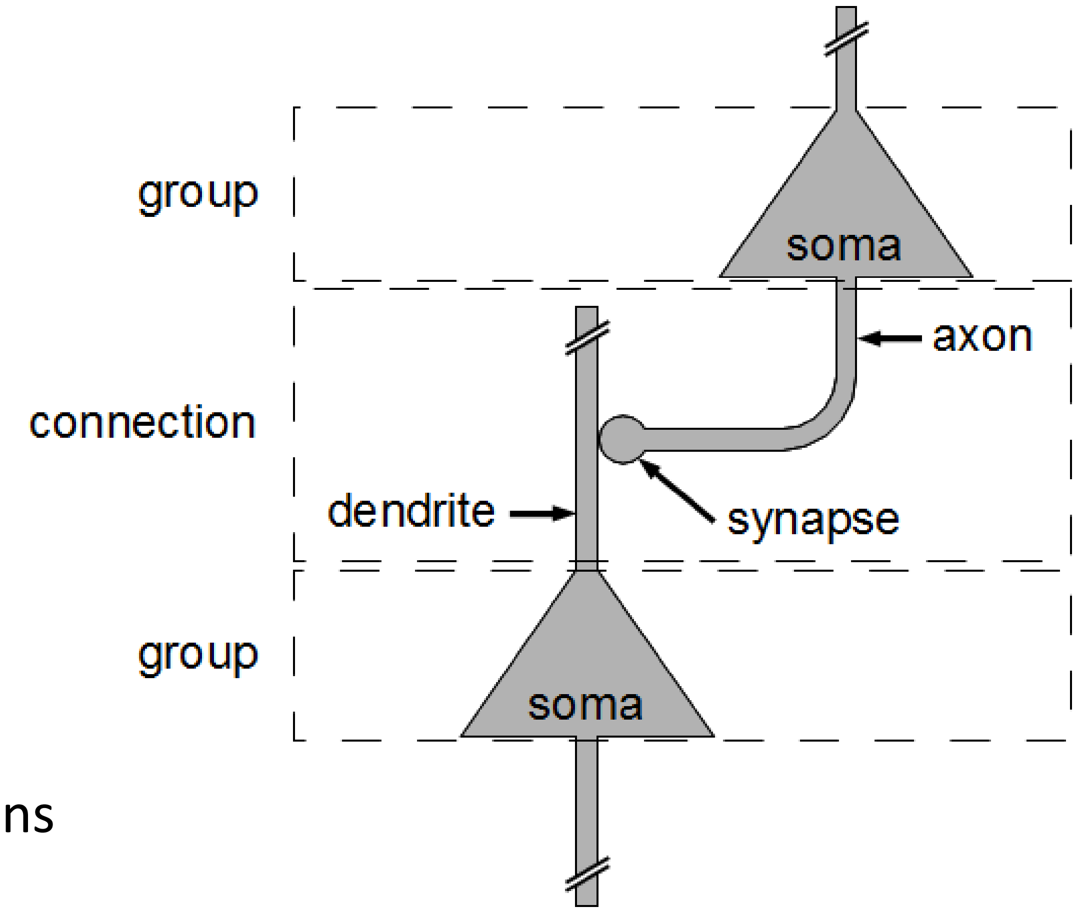
Neurons and synapses

- Group
  - Specific aggregation of neurons of identical type
- Connection
  - Feed information from group to group
  - Aggregation of synapses of identical type
  - Definition of the arrangement of the synapses
- Connection framework
  - Deals with axon, synapse, and dendrite of the neurons
  - Computational element: Synapse
- Distinction between group and connection is not a biological fact
  - An abstraction within framework that allows easier approach to modeling biological systems



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Complete definitions

- Complete definition of a connection twofold
  - Definition of the update function of the synapse
  - Definition of the connectivity
- “Connectivity” refers to the spacial layout of the axons, synapses and dendrites
- Update function and connectivity are not as easily separable:
  - The delays in the dendrites are derived from the connectivity

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Connection assumptions

- Assumptions concerning connections
  - There is no delay in axons
  - The computation takes place in synapses
  - The transmission delay is dependent on the length of the dendrite
  - Any back-propagating signals are limited to the dendrite

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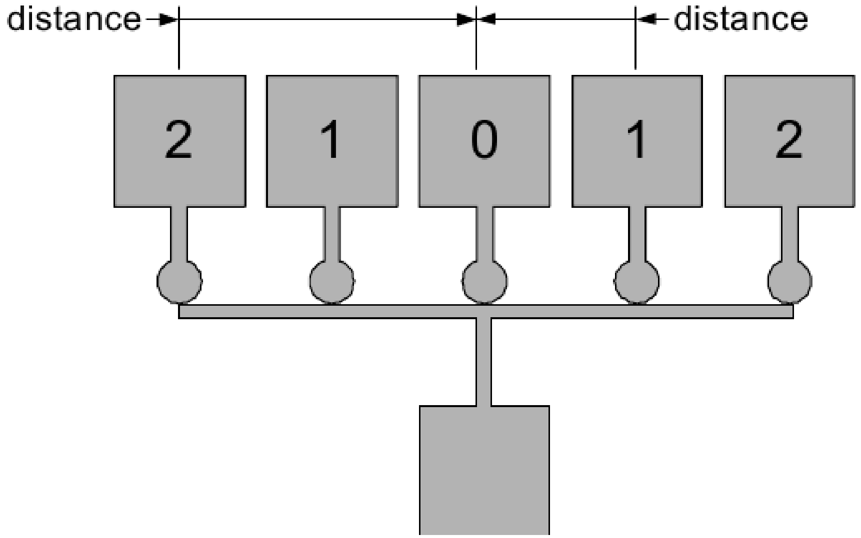
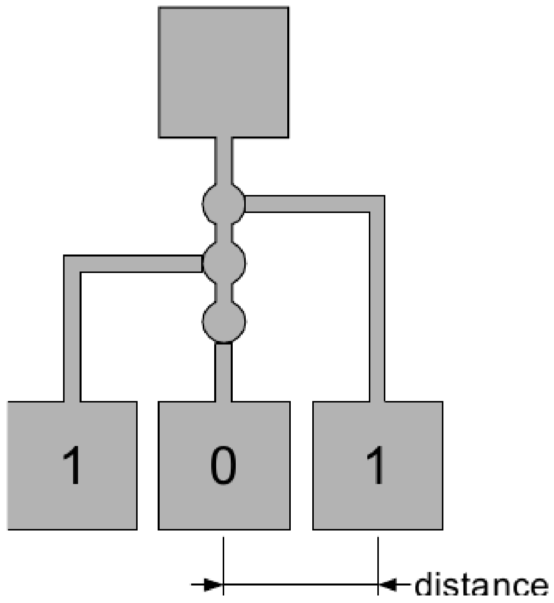
Multiplicity: RF and PF

- Possible cases:
  - "receptive field" (RF): Many-to-one
  - "projective field" (PF): One-to-many



(a) Receptive field (RF)



(b) Projective field (PF)

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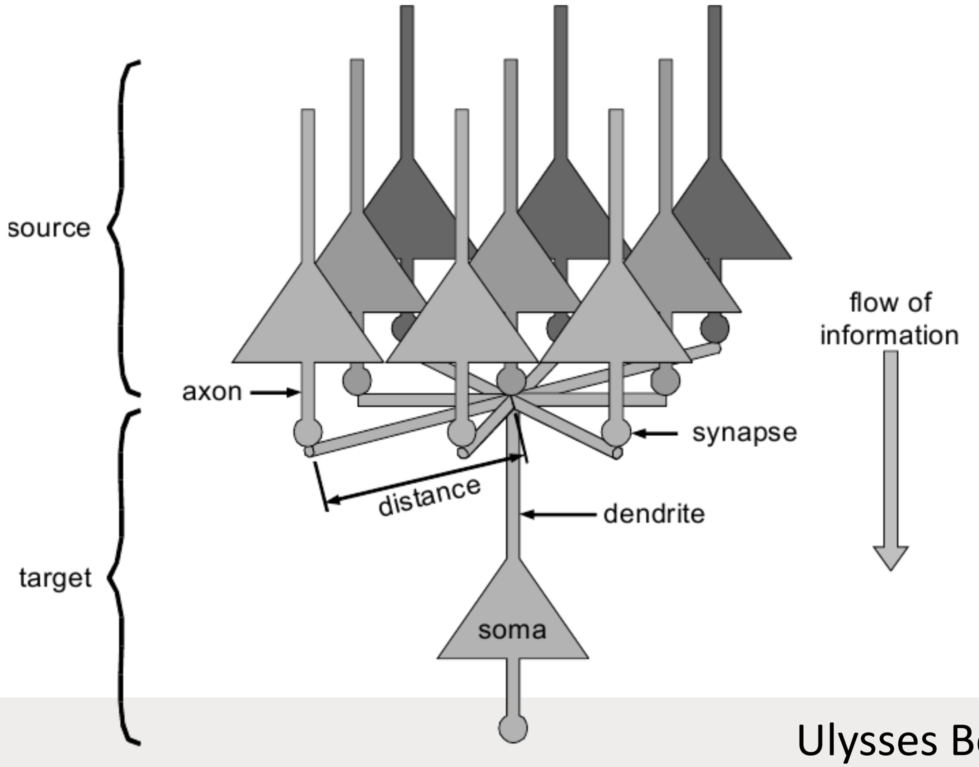
A Single nexus

- Basis of computation of the delay: Distance
- Distance = eccentricity of a neuron
- Receptive field:
  - Eccentricity is defined by the position of the sending cell relative to the position of the one receiving cell.
- Projective field:
  - Eccentricity is defined with respect of the position of the multiple post-synaptic cells relative to the one pre-synaptic neuron



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DEFINING THE CONNECTIVITY: PATTERN + ARBORIZATION

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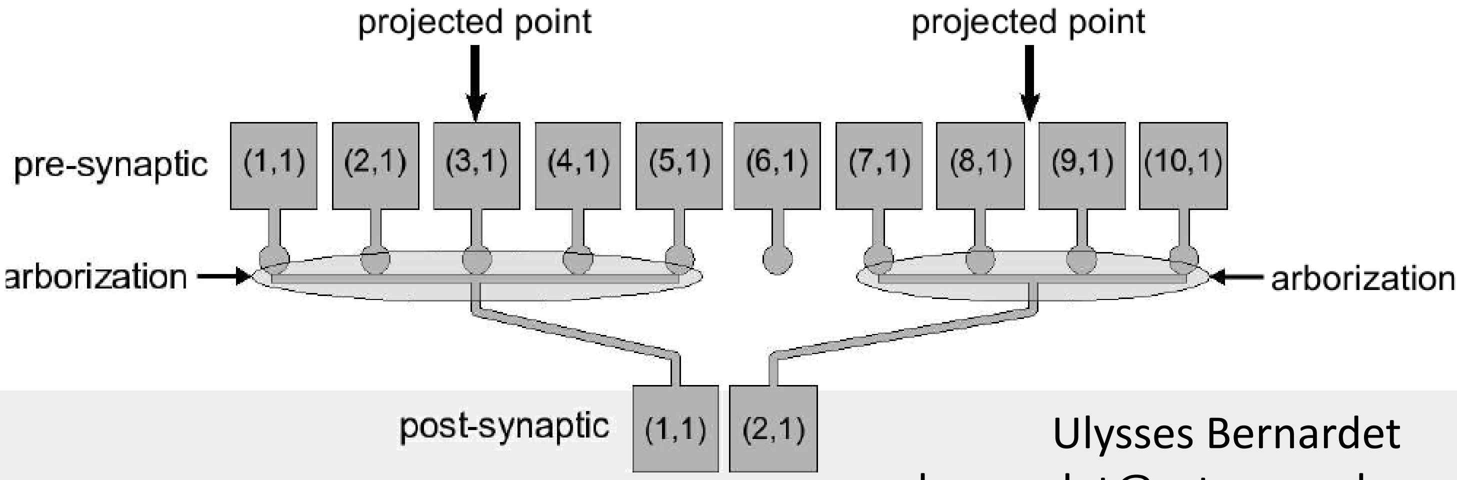
Pattern and Arborization

- Pattern
  - Defines pairs of points in the lattice of the pre- and post-synaptic group
  - Points are not neurons, but (x,y) coordinates
- Arborization
  - Defines the real neurons that send and receive input
  - Is applied to every pair of point defined by the pattern
  - Receptive field:
    - Applied to source group
  - Projective field:
    - Applied to target group



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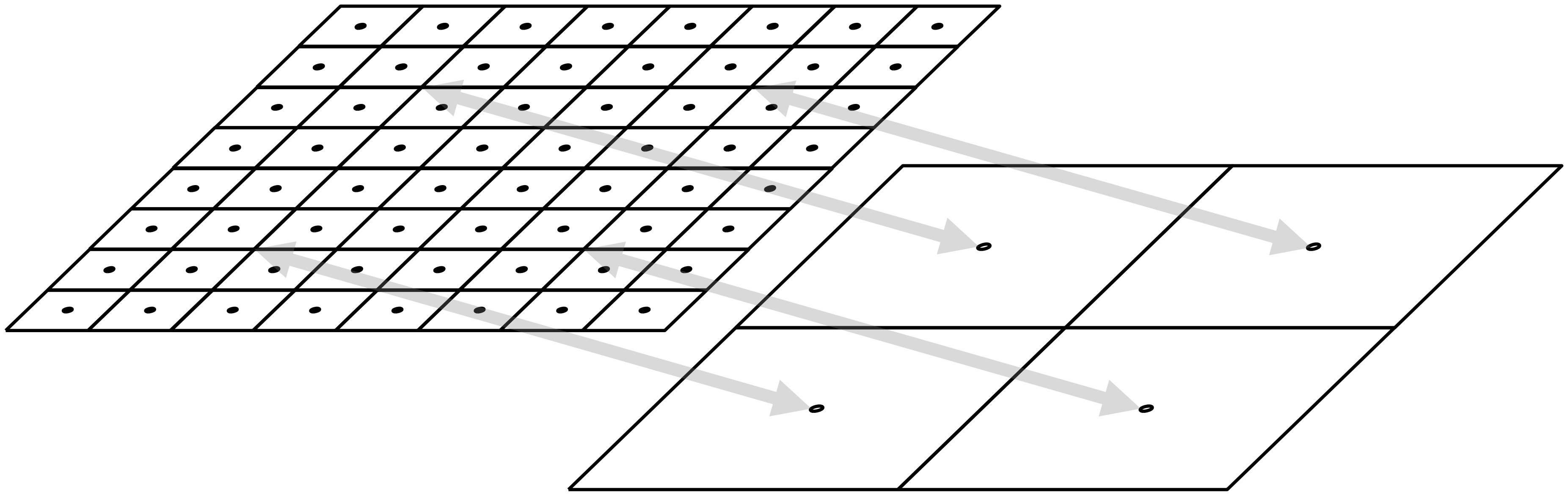
Pattern



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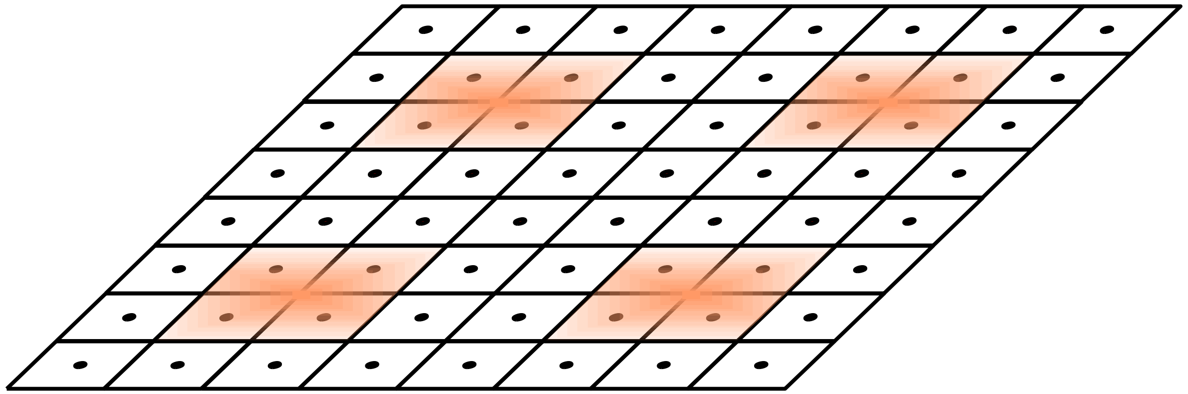
Arborization



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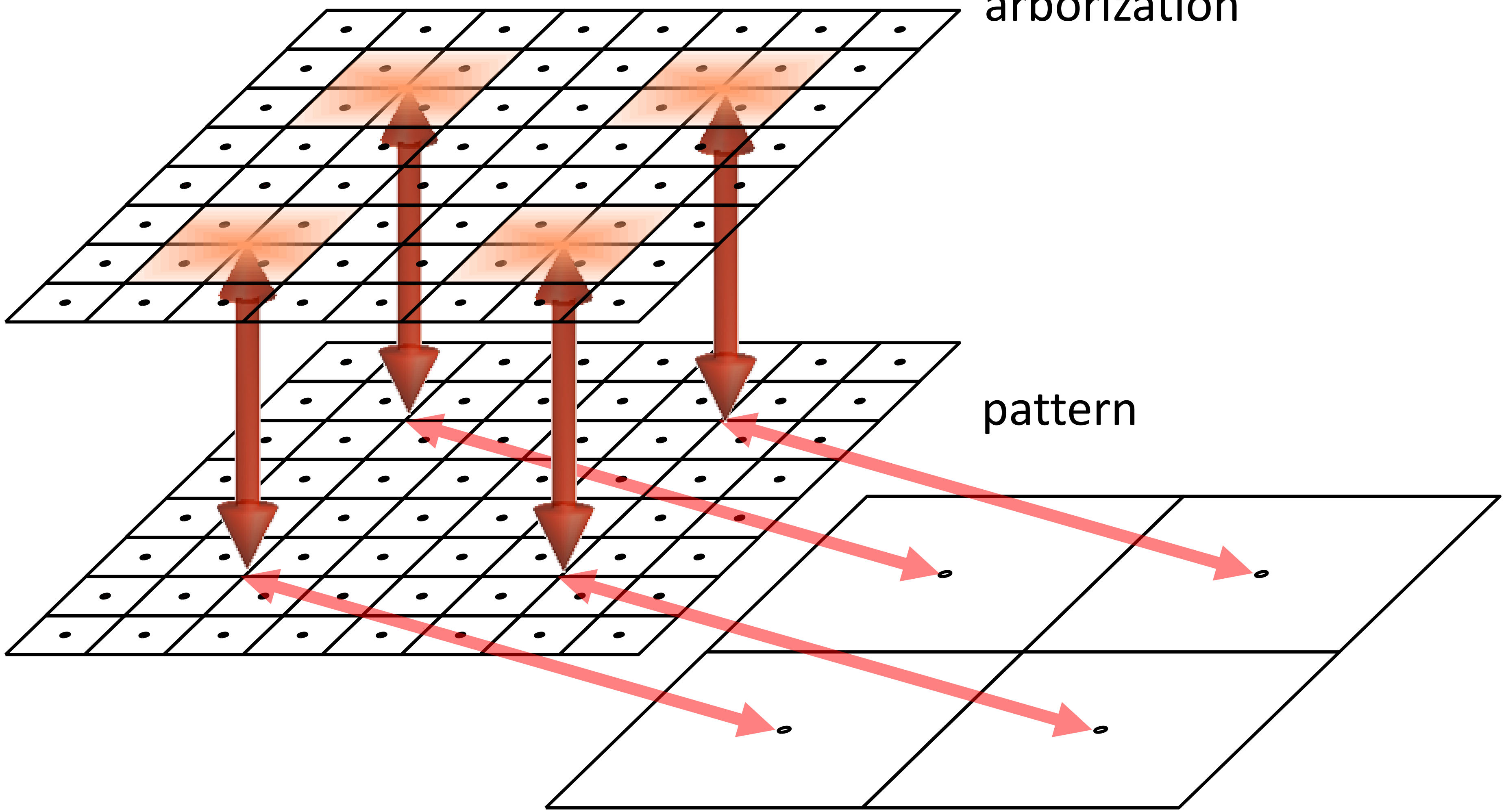
Pattern + Arborization



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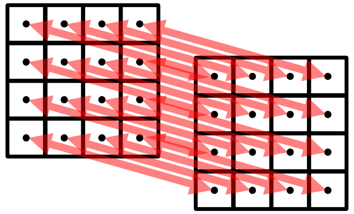
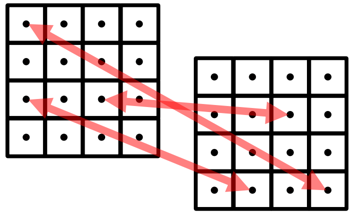
Patterns and Arborizations

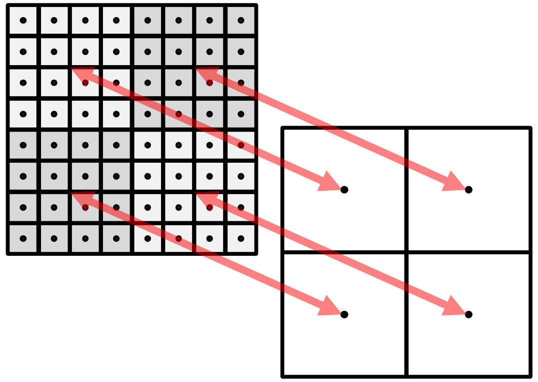
- ➔ for-each



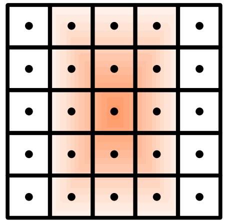
- ➔ tuples



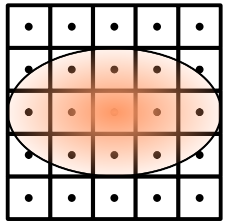
- ➔ mapped



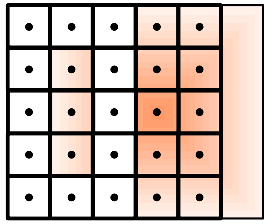
- ➔ rectangular



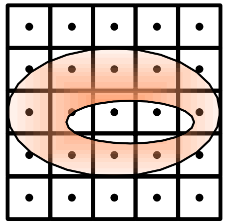
- ➔ elliptic



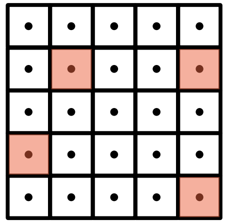
- ➔ rect. w. window



- ➔ elliptic w. window



- ➔ random



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→ Demo connections

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Demo checklist

- Pattern types
  - Mapped: All vs center
  - Creating tuples
- Arborization types
- Connection diagram

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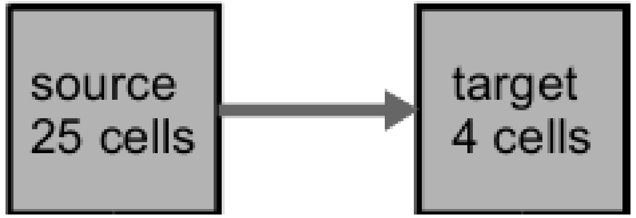
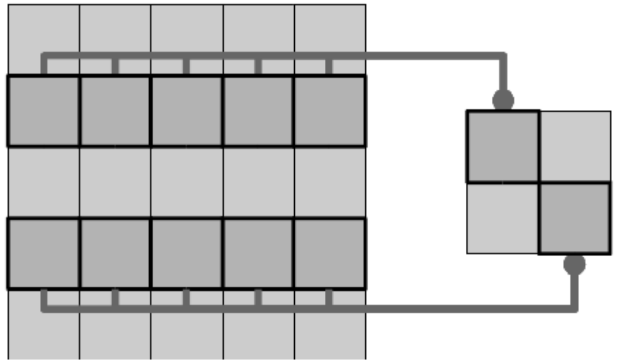
Multiplicity: The axon-synapse-dendrite nexus

- Connections are represented at three different levels
  - Process
  - Group
  - Synapse
- Multiplicity
  - Single connection is an assembly of axon-synapse-dendrite nexuses
  - Single nexus in turn can connect several pre-synaptic neurons to one post-synaptic cell, or feed information from one pre-synaptic into multiple post-synaptic neurons
- One nexus can comprise of several axons, synapses, and dendrites





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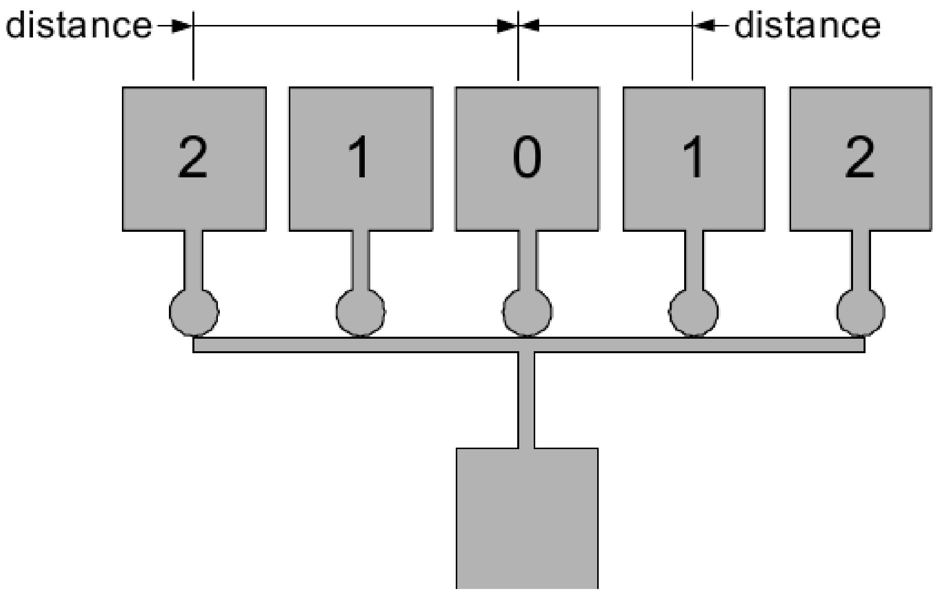
Delay function

- Used to compute delay for each synapse belonging to an arborization
- In most delay functions the calculation is depending on the size of the arborization, i.e. height/width, or outer height/outer width respectively
- Types:
  - FunLinear
  - FunGaussian
  - FunBlock
  - FunRandom
  - FunUniform



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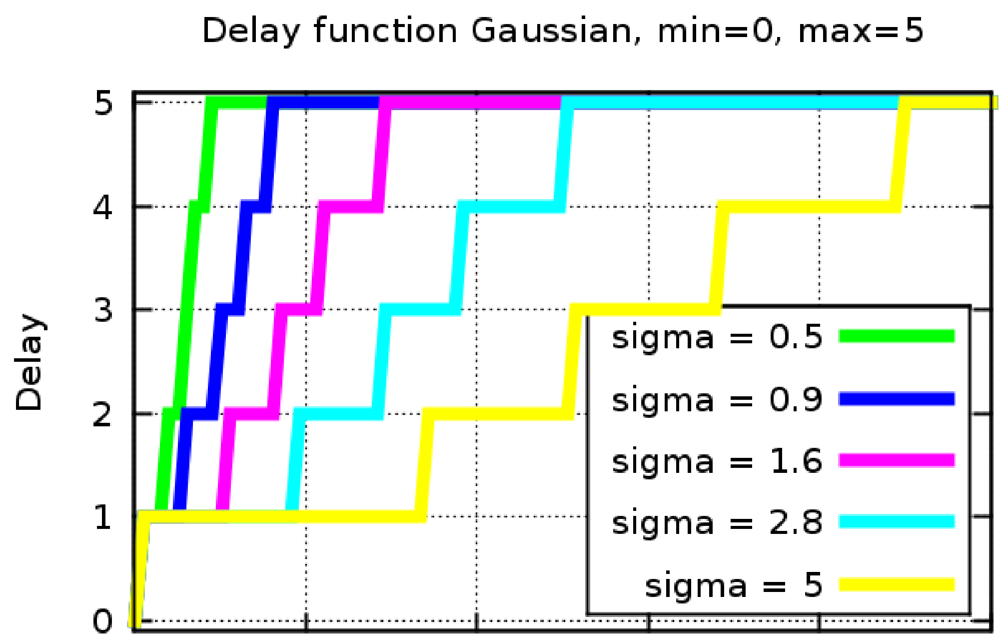
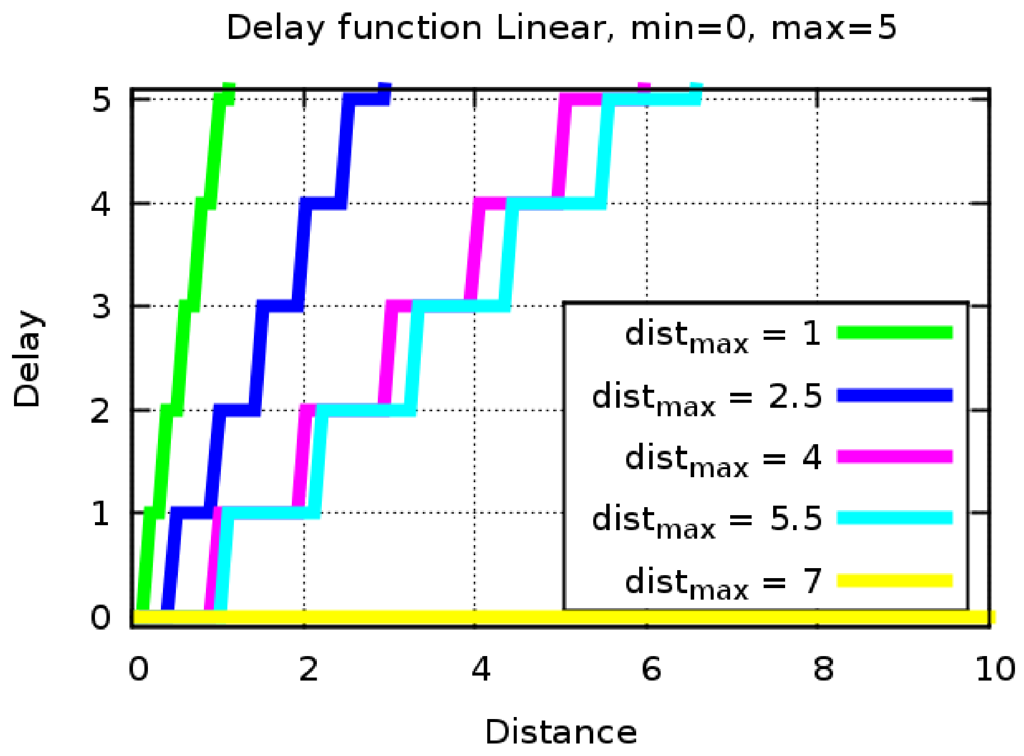
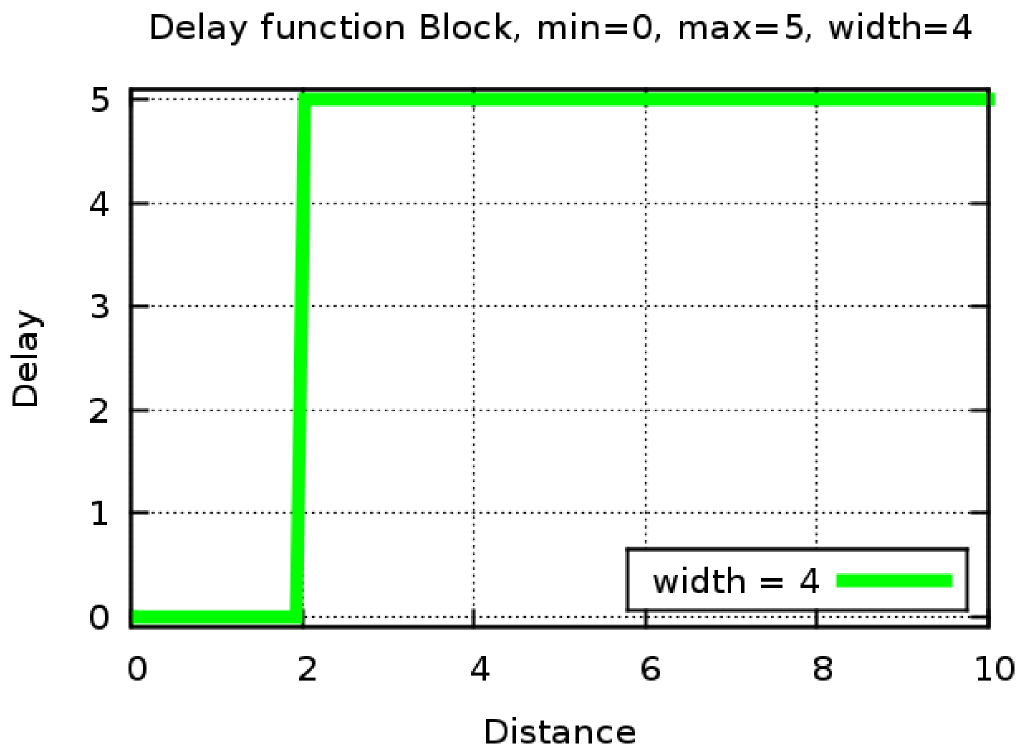
Delay function







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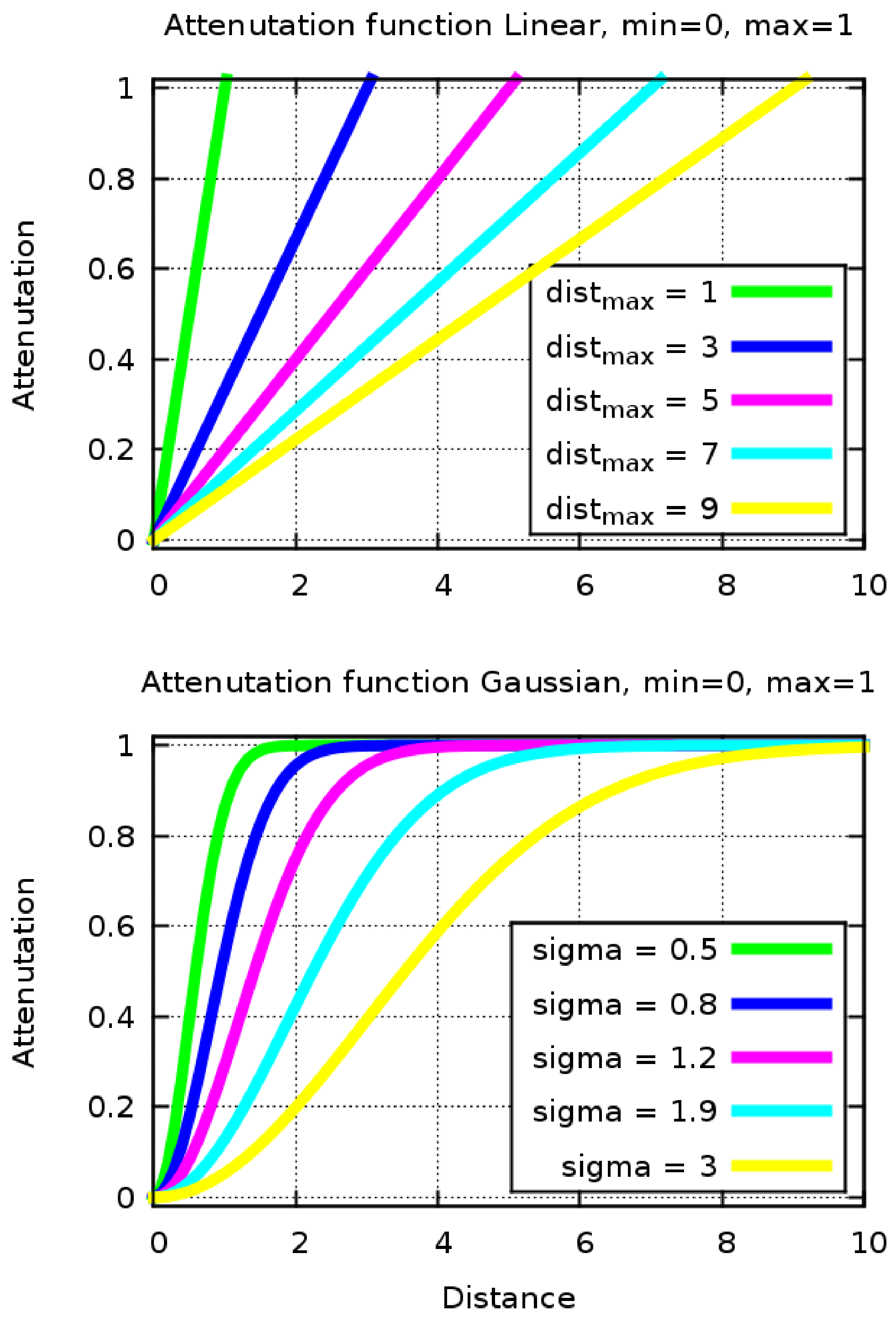
Attenuation function

- Attenuation is the “damping” of the signal on the dendrite
- Attenuation -> inverse of strength



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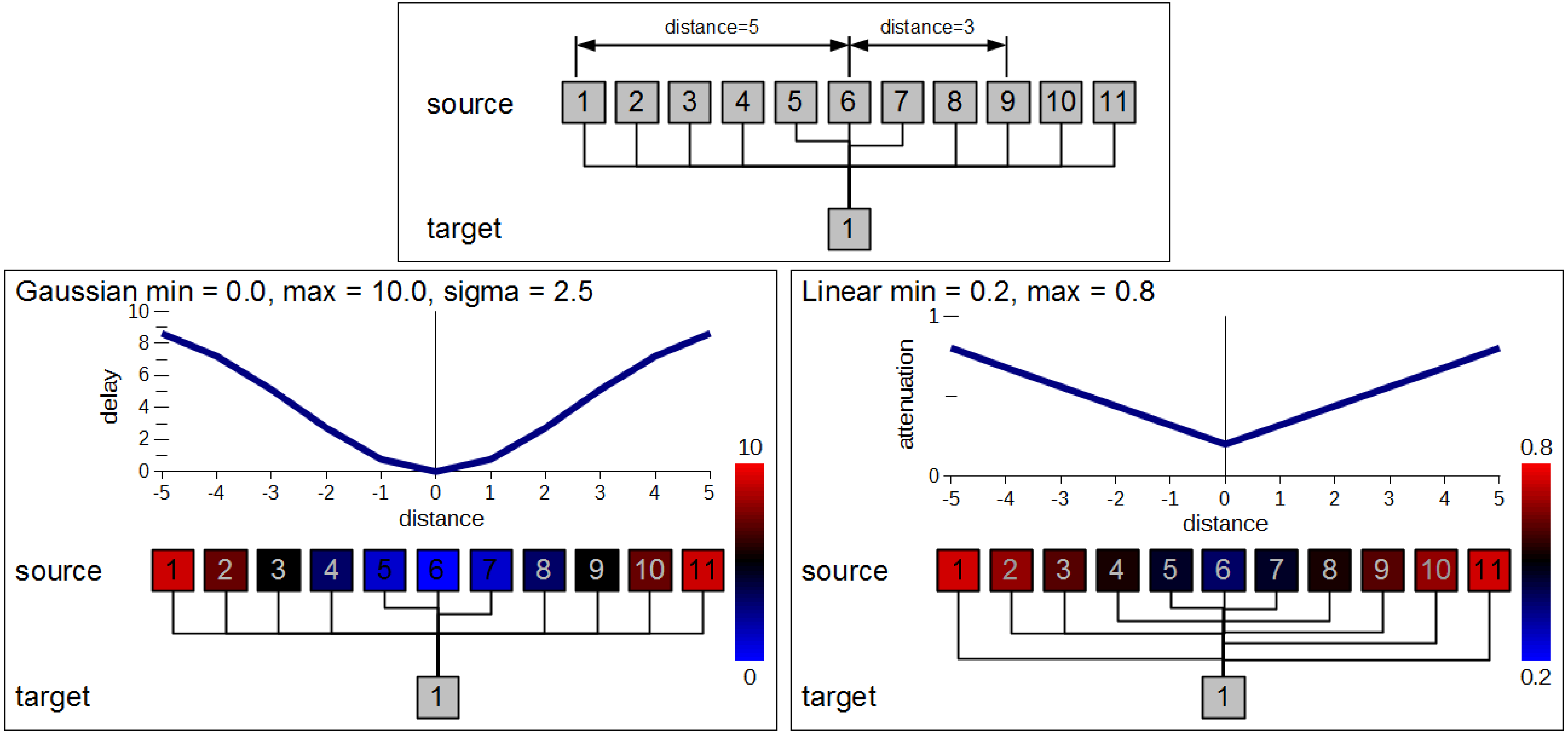
Attenuation and delay example



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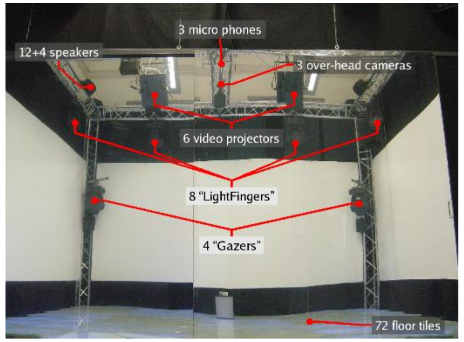
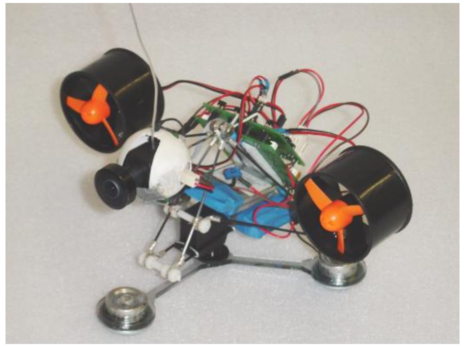
Working with Modules

iqr Modules

- A Module is a plug-in to exchange data with an external entity
  - Sensor (camera, microphone, etc.)
  - Actuator (robot, motor)
  - Algorithm
- Modules read and write the activity of groups
- One process can have only one single module



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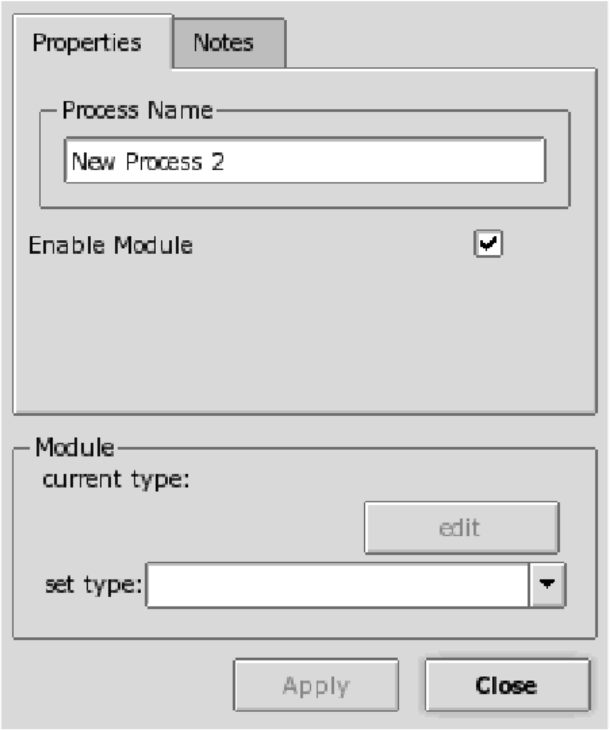
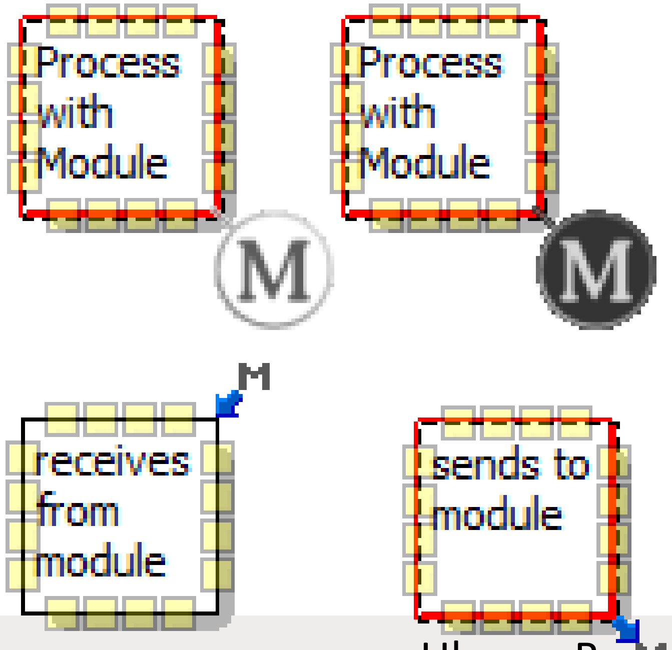
iqr Modules

- Assigning a module to a group
  - Process properties dialog
  - Select the module type
- Edit button in the Module frame → Module property dialog
- "Groups to Module" and "Module to Groups" -> contain the allocation information between modules and groups
- Disable the update of a module during the simulation:
  - un-check the Enable Module check-box in the process properties dialog





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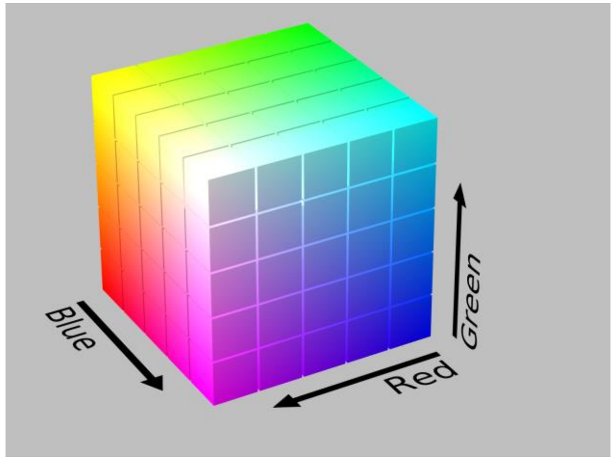
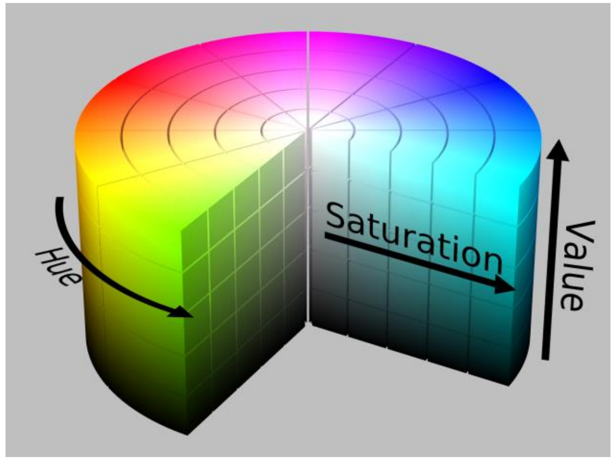
Video modules

- Module parameters
  - Monochrome
  - HSV color space

RGB color space



HSV color space



- On Linux you can use “xawtv” to check video
- Windows:
  - Module uses first camera found
  - Use virtual webcam software (e.g. Manycam) to use multiple cameras

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Other modules

- Joystick Module
- Phidgets
- Wii remote
- Speech synthesizer
- Network communication (TCP/IP, UDP, OSC)
- More at: http://sourceforge.net/projects/iqr-extension/

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AND THERE’S MORE…

- User-defined types
- Advanced features

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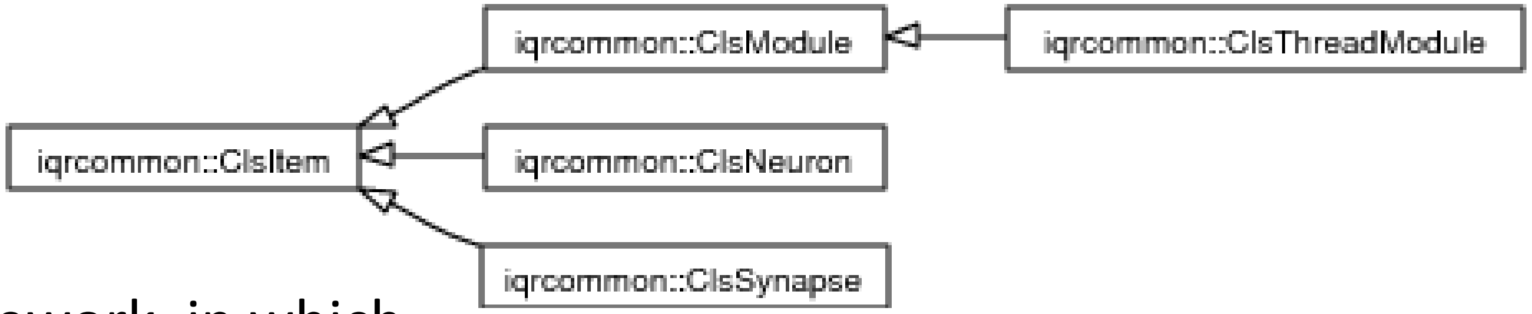
Classes for (User-defined) types

- iqr does not make a distinction between types that are defined by the user, and those that come with the installation; both are implemented in the same way
- Base-classes for all three types (neurons, synapses, modules) derived from ClsItem
- The classes derived from ClsItem are parent class for the specific types
  - E.g. a specific neuron type will be derived from ClsNeuron



- Inheritance schema defines the framework, in which
  - parameters are defined
  - data is represented and accessed
  - input, output, and feedback is added
- All types defined in namespace iqrcommon

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Programming Neurons, Synapses, Modules

- Base classes
- Class Methods (initialize, update, ...)
- Parameters
- State arrays
- Tricks about accessing history
- ...etc

iqrUserdefinedTypes.pdf

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Neuron example

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```cpp
#ifndef NEURONINTEGRATEFIRE_HPP
#define NEURONINTEGRATEFIRE_HPP

#include <Common/Item/neuron.hpp>

namespace iqrcommon {

    class ClsNeuronIntegrateFire : public ClsNeuron {
    public:
        ClsNeuronIntegrateFire();

        void update();

    private:
        /* Hide copy constructor. */
        ClsNeuronIntegrateFire(const ClsNeuronIntegrateFire&);

        /* Pointers to parameter objects */
        ClsDoubleParameter *pVmPrs;
        ClsDoubleParameter *pProbability, *pThreshold;

        /* Pointers to state variables. */
        ClsStateVariable *pVmembrane, *pActivity;
    };
}

#endif
```

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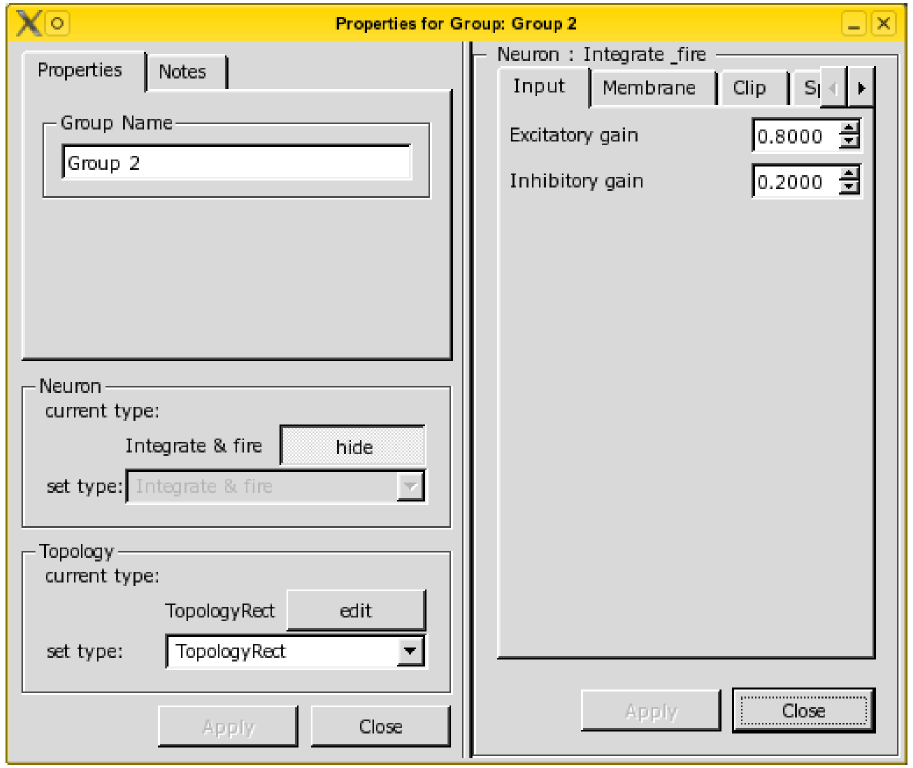
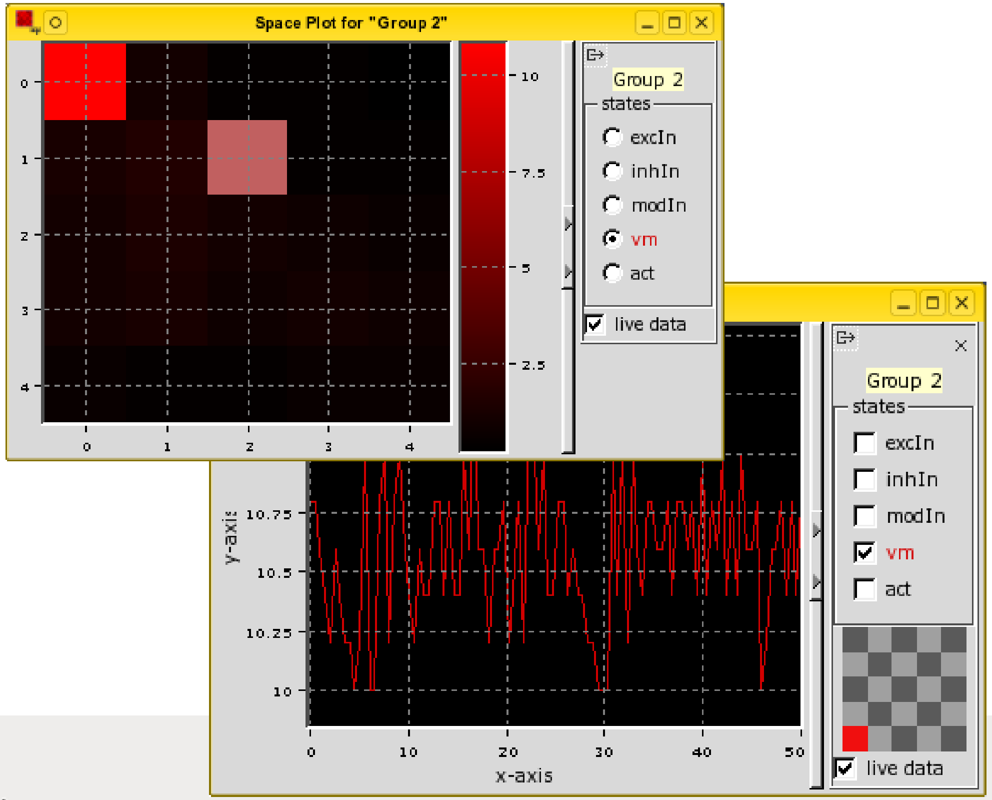
```cpp
#include "neuronIntegrateFire.hpp"

MAKE_NEURON_DLL_INTERFACE(iqrcommon::ClsNeuronIntegrateFire, "Integrate & fire")

iqrcommon::ClsNeuronIntegrateFire::ClsNeuronIntegrateFire()
    : ClsNeuron(), pVmembrane(0), pActivity(0) {

    pExcGain = addDoubleParameter("excGain", "Excitatory gain",
                                  1.0, 0.0, 10.0, 4, "Gain of excitatory inputs.");

    pInhGain = addDoubleParameter("inhGain", "Inhibitory gain",
                                  1.0, 0.0, 10.0, 4, "Gain of inhibitory inputs.");

    pVmPrs = addDoubleParameter("vmPrs", "Membrane persistence",
                                0.0, 0.0, 1.0, 4, "Proportion of the membrane potential");

    pProbability = addDoubleParameter("probability", "Probability",
                                      0.0, 0.0, 1.0, 4, "Probability of output occuring");

    /* Add state variables. */
    pVmembrane = addStateVariable("vm", "Membrane potential");
    pActivity  = addOutputState("act", "Activity");
}

void iqrcommon::ClsNeuronIntegrateFire::update() {
    StateArray &excitation = getExcitatoryInput();
    StateArray &inhibition = getInhibitoryInput();
    StateArray &vm         = pVmembrane->getStateArray();
    StateArray &activity   = pActivity->getStateArray();

    double excGain     = pExcGain->getValue();
    double inhGain     = pInhGain->getValue();
    double vmPrs       = pVmPrs->getValue();
    double probability = pProbability->getValue();

    /* Calculate membrane potential */
    vm[0] *= vmPrs;
    vm[0] += excitation[0] * excGain;
    vm[0] -= inhibition[0] * inhGain;

    activity.fillProbabilityMask(probability);
    /* All neurons at threshold or above produce a spike. */
    activity[0][vm[0] >= 1.0] = 1.0;
    activity[0][vm[0] <  1.0] = 0.0;
}
```

Neuron example

```
ClsDoubleParameter *pExcGain =
        addDoubleParameter("excGain",
        "Excitatory gain",
        1.0, 0.0, 1.0, 3,
        "Gain of excitatory inputs.\n"
        "The inputs are summed before\n"
        "being multiplied by this gain.",
        "Input");
```






```
ClsStateVariable *pVmembrane =
        addStateVariable("vm",
        "Membrane potential");
```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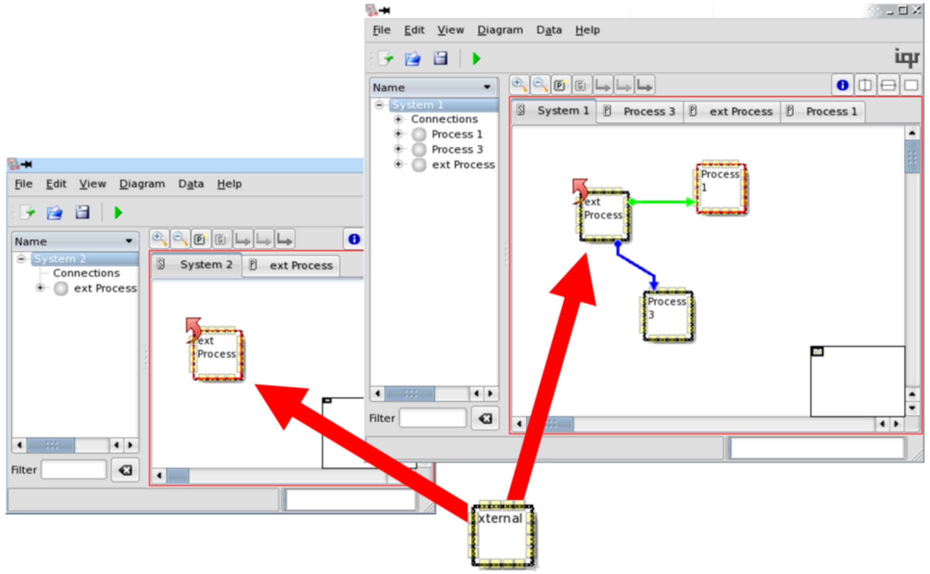
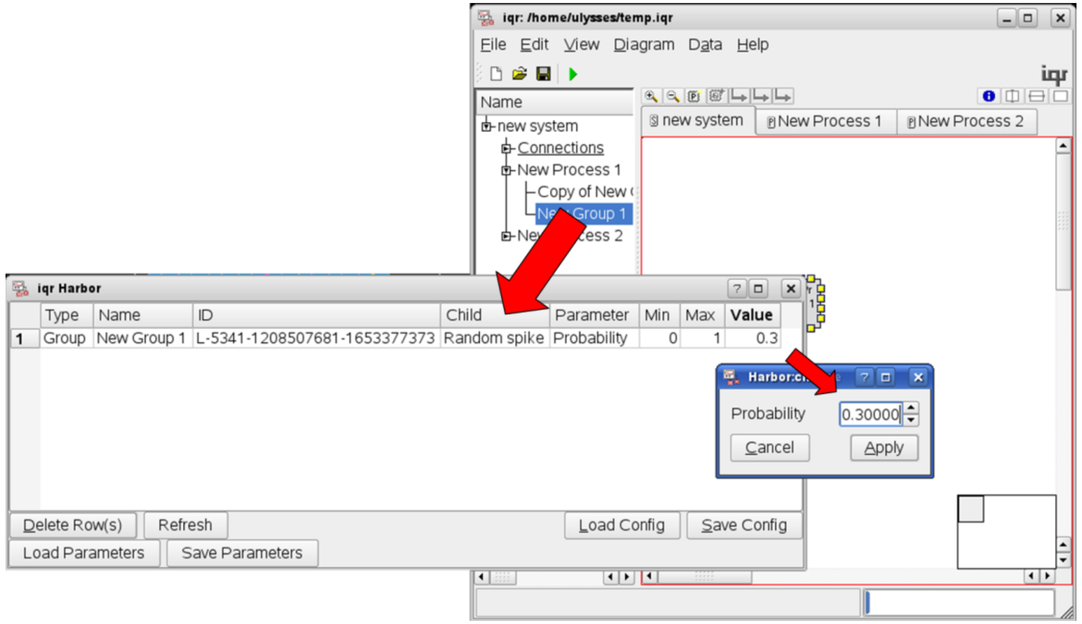
Advanced features

- External Processes
  - Process + connections defined in separate file
  - Import or link-in Process definition
- Harbor
  - Collect items
  - Change items in single place
  - Make items available to Module
- Optimization
  - Access to system elements from Modules
- Remote control
  - UDP and GUI





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Importance of constraints

- The synthetic approach as necessary, but not sufficient basis for the development of meaningful models

- Apply constraints to the elements of the model
  - Structural constraints from biology
  - Computational constraints from biology
  - Behavioral constraints from psychology / ethology

- Embodied agents provided task and scope relevant constraints

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Starting iqr

- From menu iqr
- Command line arguments

-f <filename> --file <filename>	open system file <filename>
-c <filename> --config <filename>	open configuration file <filename>
-r --run	automatically start simulation
-v --version	show version

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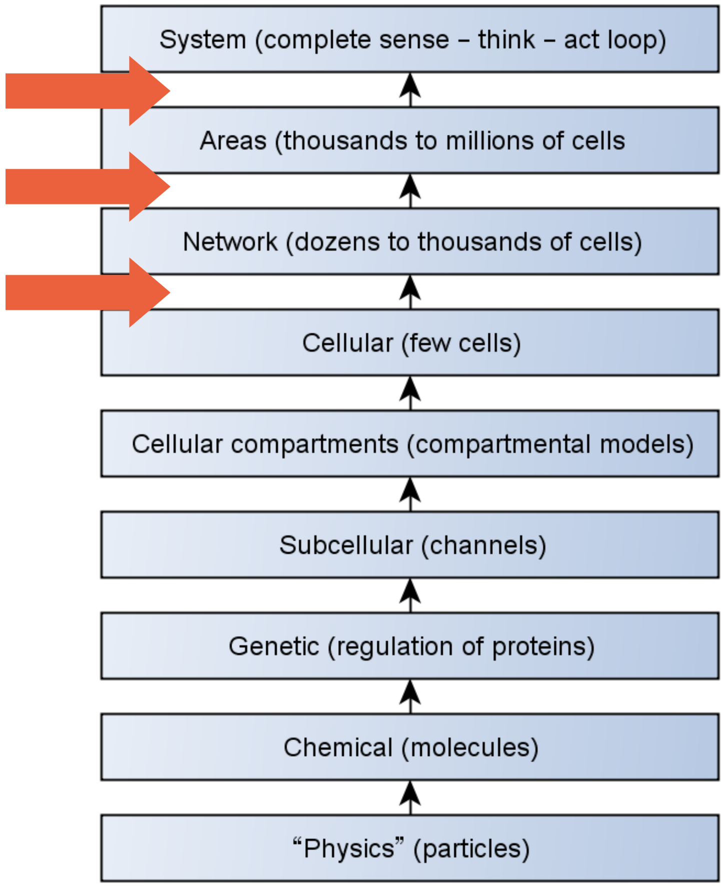
The “neuro-architectural” approach

- Information-flow approach that integrates
  - Structural and computational constraints from biology
  - Control principles from systems theory
  - Behavioral constraints from psychology / ethology
- Systems perspective → Functional goal (needed for behavioral constraints)

- If we want to build systems able to generate a meaningful behavior in the real world system have to be complete:
  - Span from sensory processing to the behavioral output
  - Systems compliant with this requirement will inevitably be of a large-scale, where the overall architecture is of critical importance



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