Nature-inspired Smart Information Systems

Brainstorming Meeting, 8th/9th June 2006, Palma de Mallorca

Nature-inspired
Systems Modelling, Optimisation and Control:
Status quo & quo vadis?
The Evolutionary View

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Brainstorming

Brainstorming is a creative thinking technique.

Alex Osborn, advertising writer of the 1950s and 1960s, has contributed many powerful creative thinking techniques. Brainstorming is probably the best known and certainly one of the most powerful (see his book *Applied Imagination*).

Who? What? When? Where? Why? How?

These questions are especially useful for generating ideas for improving something (the evolutionary approach), but they also help to break thinking out of the evolutionary mode and put it into the revolutionary mode by returning the thinker to the origin and purpose of the idea or solution. By returning to the roots of the problem, a new vision can be created.

Brainstorming

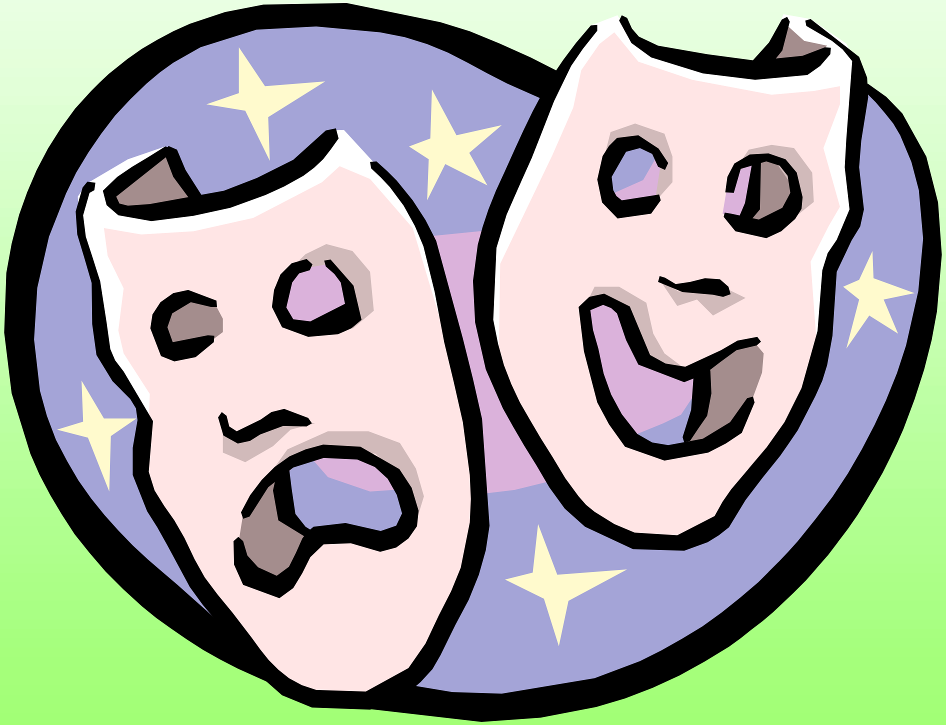
- Brainstorming is an evolutionary process.
- Brainstorming is a combination of population (evolutionary) and individual (neural) learning.
- Brainstorming is a cooperative process of mutual optimisation in social interaction. Best results are obtained for balanced proportions of diverse agent types.
- Brainstorming is similar to genetic programming.
- Brainstorming is similar to scatter search.
- Brainstorming is extended swarm intelligence.
- Brainstorming is collective decision making.
- Brainstorming is nature-inspired cooperative problem solving.

Setting the Scene for NiSIS

‘Setting the Scene‘ has three meanings:

- to bring about, accomplish, contrive sth.
- to set an example, to set a task
- to take all the measures to stage a play (by playwright, stage-manager, actors, scenic designer, properties manager, prompter, stage-setter, stage-hand)

Setting the Scene for NiSIS



Setting the Scene for NiSIS

Play	**NiSIS**	3 Simultaneous Acts
1 NiDT	**2 NiN**	**3 NiMOC**
Play Script	NiSIS Roadmap	
Playwright	*Derek A. Linkens*	ITB
Stage-Manager	*Karl Lieven*	ELITE
Scenic Designer	*Karl Lieven*	ELITE
Properties Manager	*Jens Strackeljan*	TTE
Prompter	*Sascha Jovanovic*	TTE
Stage-Setter	*Jan Jantzen*	TTE
Stage-Hand	*Eva-Maria Lenart*	ELITE

Setting the Scene for NiSIS

Acts	**Principal Parts**	**Principal Actors**
NiDT	Leading Man 1	*Davide Anguita*
NiDT	Leading Man 2	*Bogdan Gabrys*
NiN	Leading Man 1	*Trevor Martin*
NiN	Leading Man 2	*Nick Monk*
NiMOC	Leading Man 1	*Reinhard Guthke*
NiMOC	Leading Man 2	*Ronald Westra*

Nature-inspired Systems Modelling, Optimisation and Control (NiMOC)

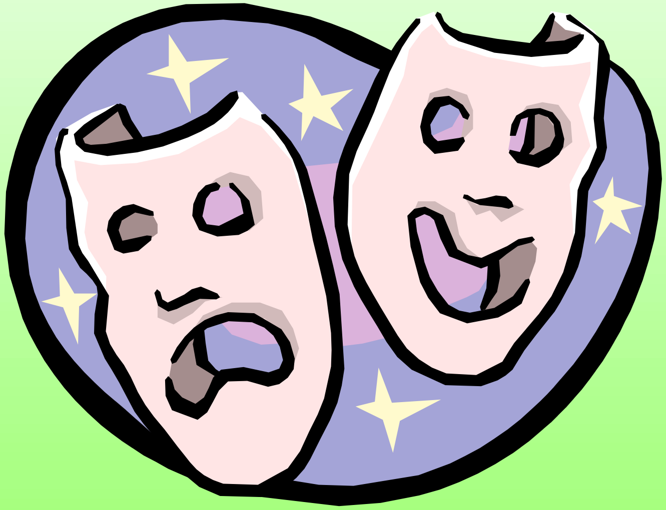
Founding Actors

Chair: Reinhard Guthke, Co-Chair: R. Westra

Name	Part	Affiliation	Country
Karl Bayer	Biotechnology	University of Natural Resources and Applied Life Sciences Vienna	Austria
Jon Garibaldi	Computer Science & IT	University of Nottingham	United Kingdom
Reinhard Guthke	Molecular & Applied Microbiology, BI & SB	Hans Knoell Institute Jena	Germany
Kauko Leiviskä	Process & Environ-mental Engineering	University of Oulu	Finland
Teresa Mendonca	Mathematics	University of Porto	Portugal
Michael Pfaff	Biotechnology & IT Applications	BioControl Jena GmbH	Germany
Mannes Poel	Research	University of Twente	The Netherlands
Ronald Westra	Mathematics & Systems Control	University of Maastricht	The Netherlands

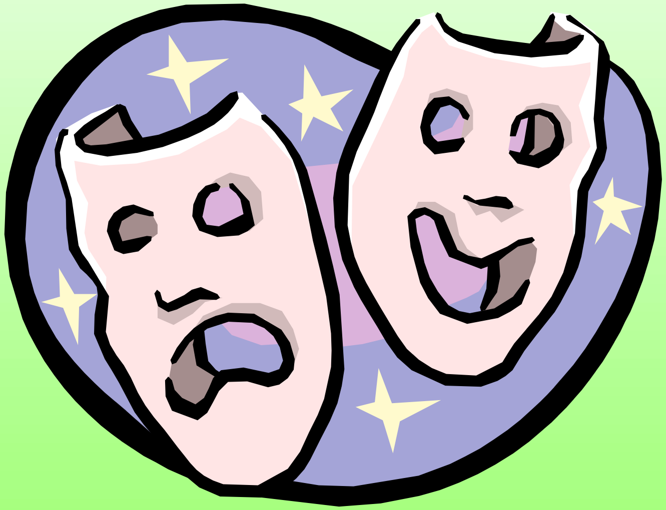
The Play

NiMOC Act



The Play

What is NiMOC about and what is its *status quo?*



Nature-inspired Systems Modelling, Optimisation and Control (NiMOC)

NiMOC efforts are to bring together **Information Technology** with the **Life Sciences**, in particular with the still emerging field of **Systems Biology** as a specific focused area of application of systems **Modelling, Optimisation and Control**.

In the Life Sciences today a **holistic view to understand how an organism works** is increasingly required and dealt with by the emerging **multi-disciplinary and multi-laboratory concept** of Systems Biology.

This **holistic view supported by systems theory** becomes **more and more realistic** due to the availability of 'post-genomic' technologies: **genomics, transcriptomics, proteomics, metabolomics, cytomics and physiomics**.

Modelling of the structure and the dynamics of interactions between different components, e.g. within **gene regulatory networks, signal transduction networks and metabolic networks**.

Extraction of hypotheses about interaction networks from experimental data in genomics, transcriptomics and proteomics as well as metabolomics and cytomics and subjection of these hypotheses to **systems modelling** that can then, in the next step, be used for **experimental design and validation**.

Technologies for Genome-wide Analysis

Allowing ...

DNA

Transcription

mRNA

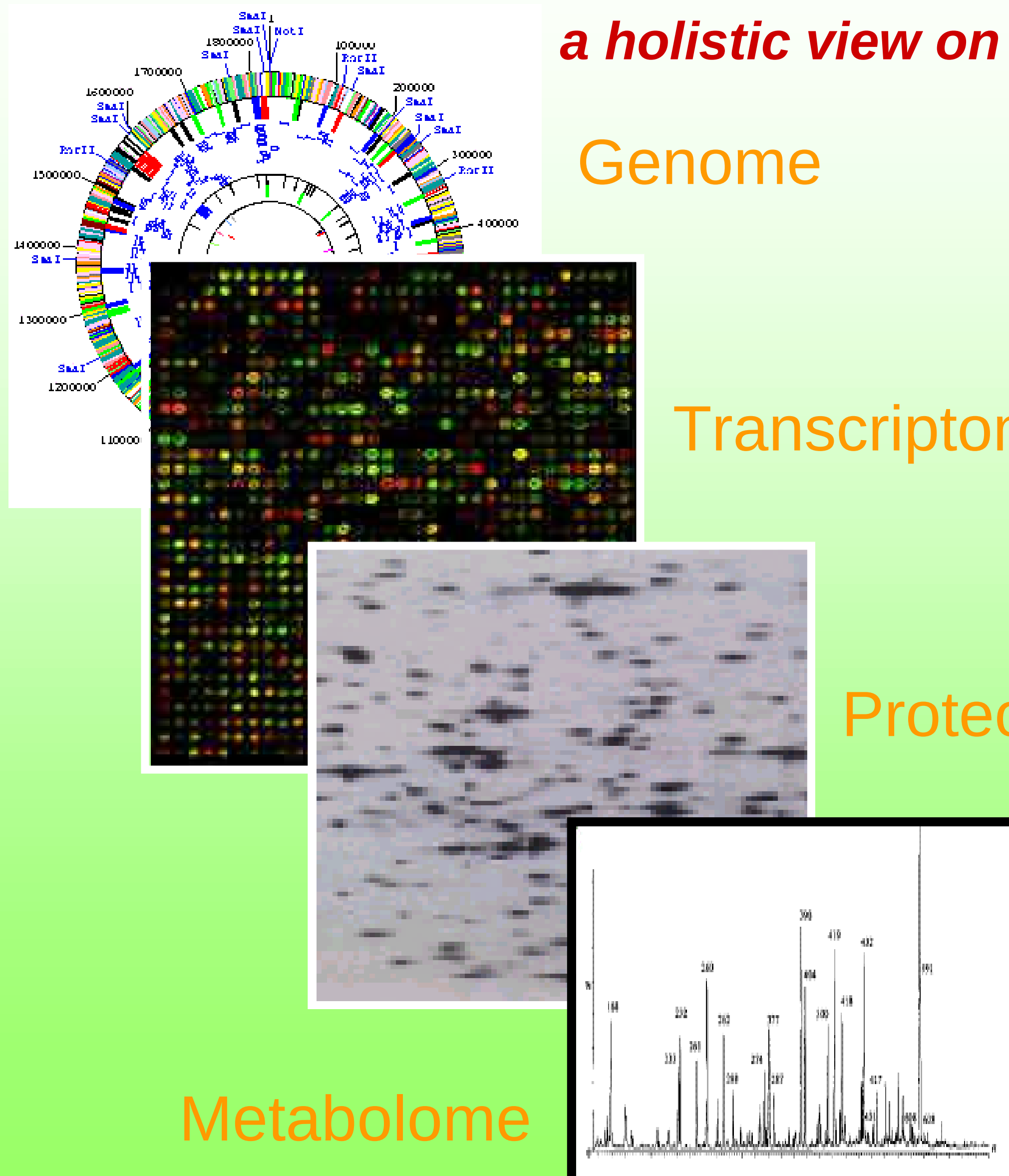
Translation

Protein

Biochemical Reaction

Metabolite

a holistic view on ...



Genome

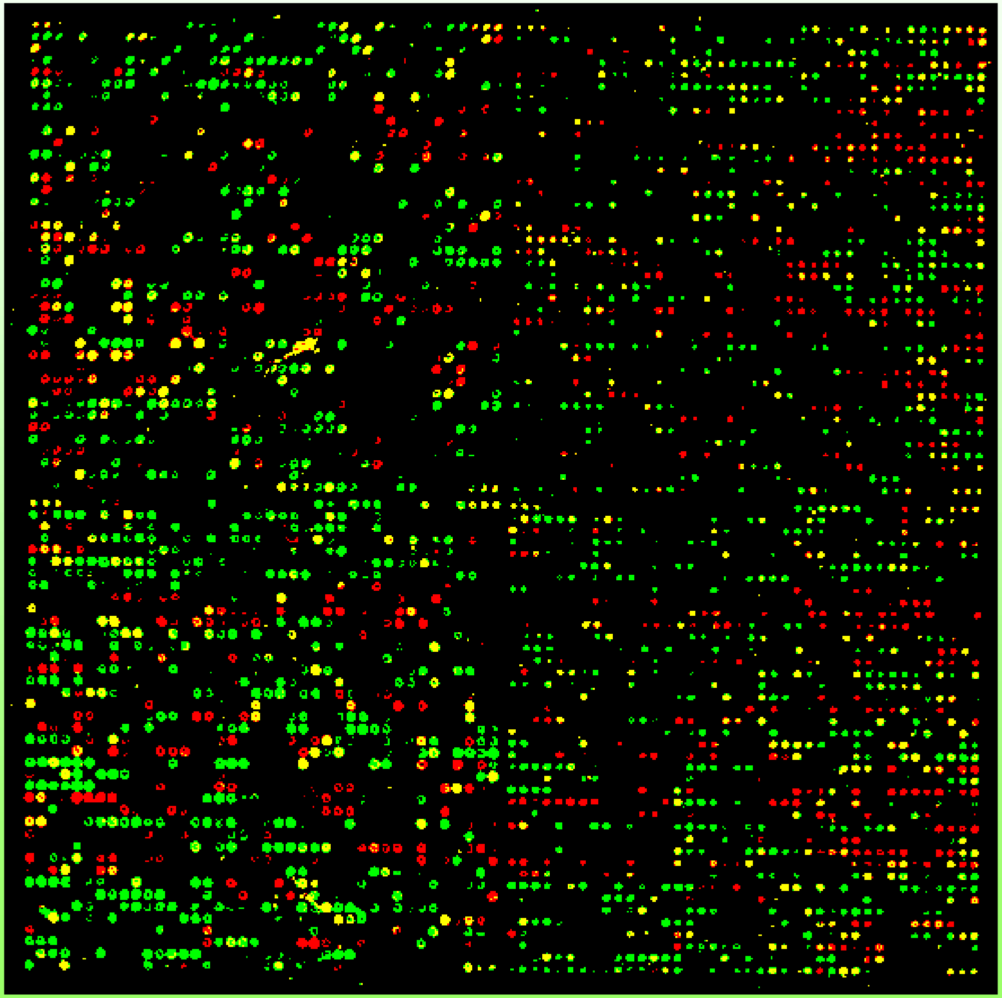
Transcriptome

Proteome

Metabolome

Milestone 1997:

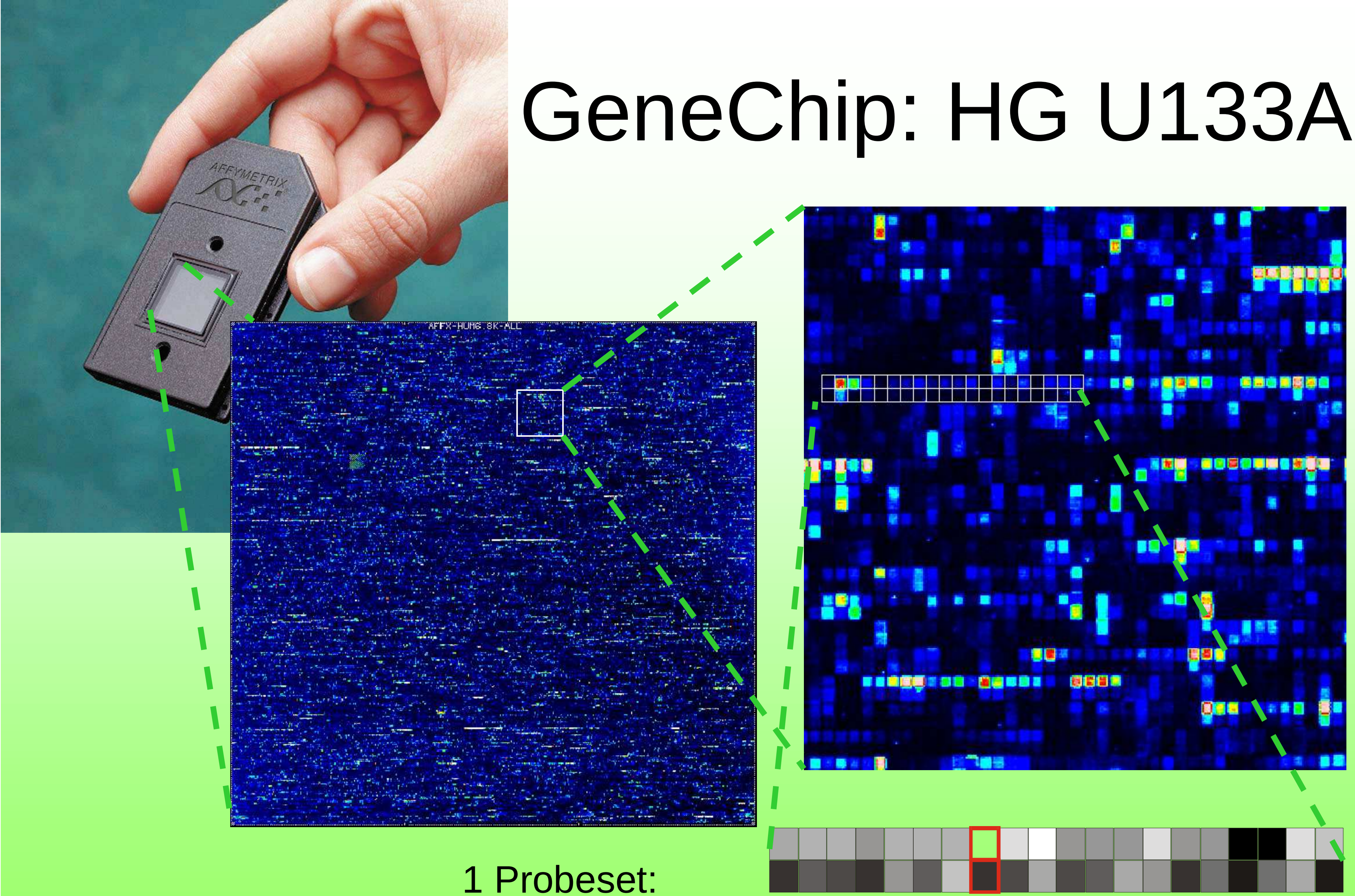
Patrick Brown's Yeast Chip



De Risi et al., *Science*, Vol 278, 1997

6400 Spots, 6116 Genes
Saccharomyces cerevisiae

GeneChip: HG U133A



100 Samples/Array * 22.000 Probesets * 40 Probes * 100 Pixels = 10^{10} Data

Nature-inspired Systems Modelling, Optimisation and Control (NiMOC)

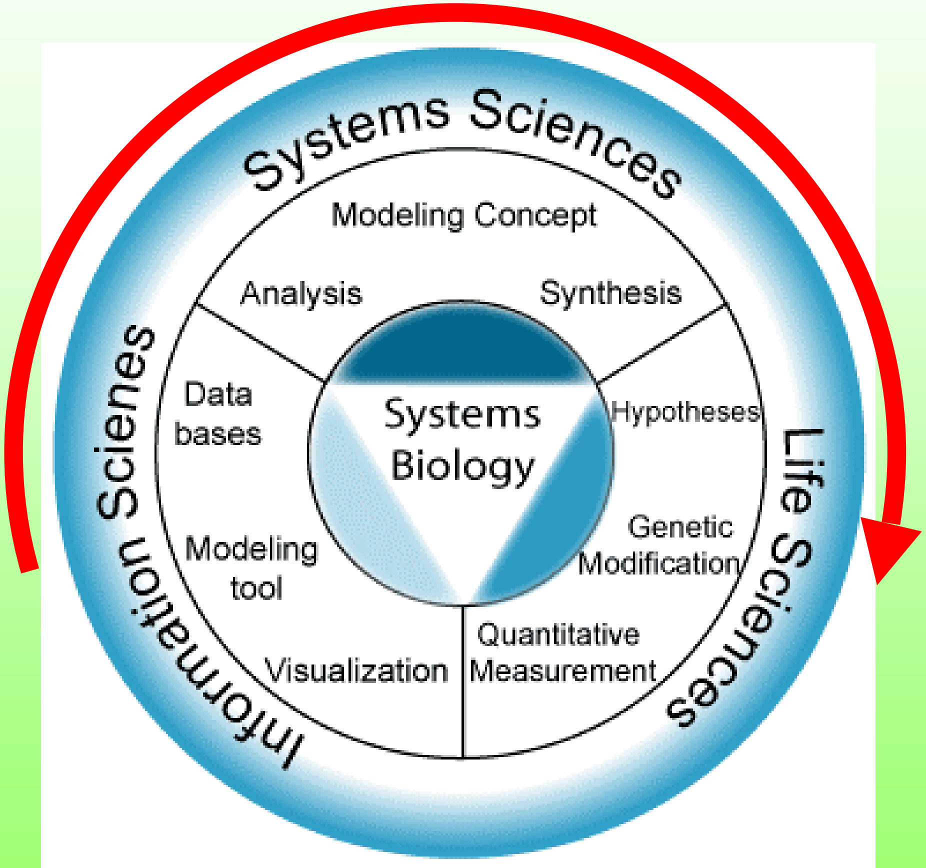
Nature-inspired Modelling, Optimisation and Control is **dedicated to the investigation of intelligent paradigms existing in nature and studied by systems approaches**, such as Systems Biology, in order **to learn from them how to better design smart**, i.e. intelligent, adaptive and advanced **information systems**.

Within NiSIS, **these systems approaches** (in particular data-driven top-down approaches) can therefore be (only) considered **essential first steps** to elucidate and reconstruct some of the principles that govern information processing in nature in order **to proceed towards the design of more advanced artificial information systems in the next steps**.

Systems Biology

Approach
to understand Nature
<u>using</u> the
Information & Systems Sciences

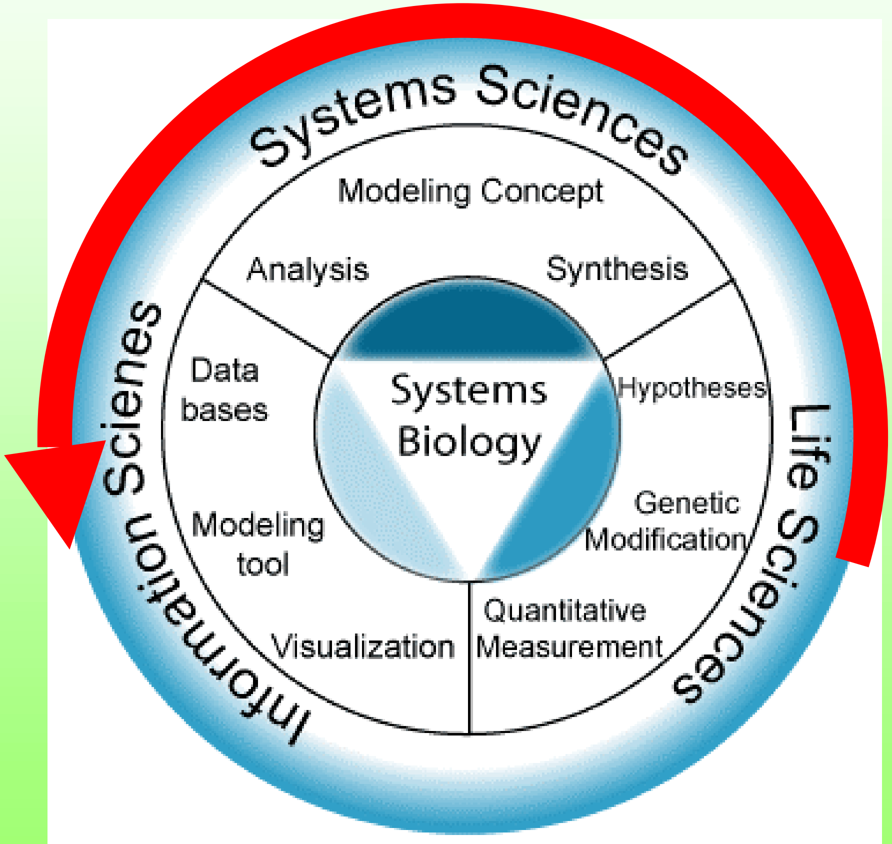
Information & Systems Sciences
serving the
Life Sciences



Nature-inspired Smart Information Systems

Approach
to understand Nature
<u>aiming at</u> the
Information & Systems Sciences

Life Sciences
serving the
Information & Systems Sciences



Modelling in Biology & Medicine

Causes → Biochemical Mechanisms → Effects

What mathematical framework
is appropriate for such an analysis?   It depends ...

a) Detailed knowledge of biochemical mechanisms

$\rightarrow$ **Forward Modelling**

(primarily knowledge-driven)

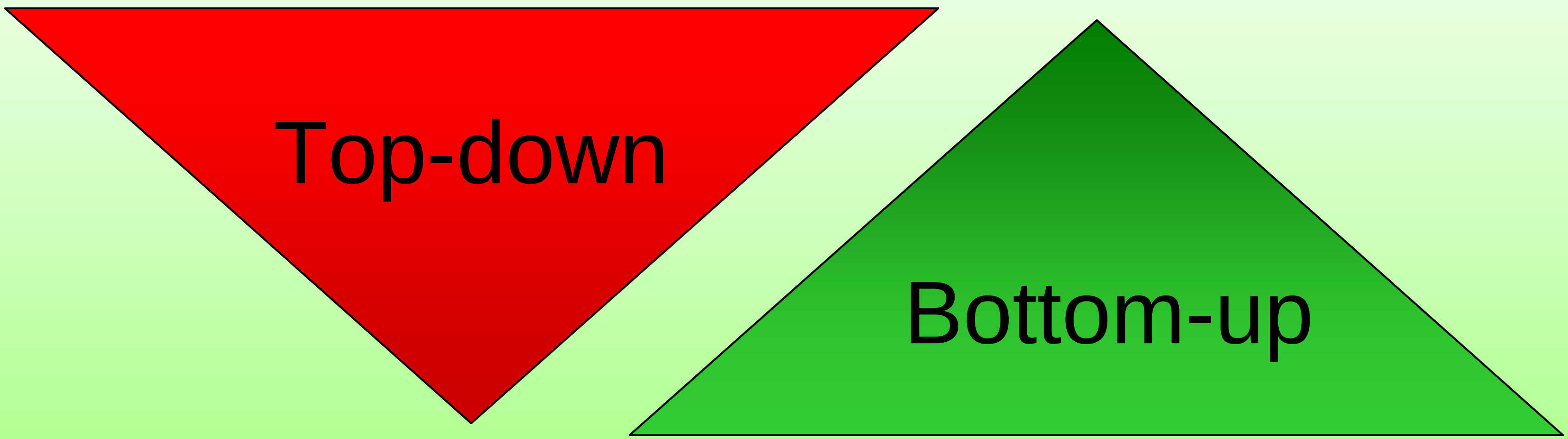
b) Data imply connectivities,
but molecular details are (still) unknown

$\rightarrow$ **Inverse Modelling, *Reverse Engineering***

(primarily data-driven, provides hypotheses)

Data-driven, inductive

analysing whole systems
in a global way
to extract hypotheses
about unknown relationships
between system components



Knowledge-driven, deductive

analysing sub-systems
in a detailed way
to finally merge them
to entire system descriptions

Nature-inspired Systems Modelling, Optimisation and Control (NiMOC)

With the availability and ever increasing amounts of genomic, transcriptomic, proteomic and metabolomic data from living systems, **top-down data analysis and modelling approaches are increasingly required to complement bottom-up approaches in Systems Biology today**.

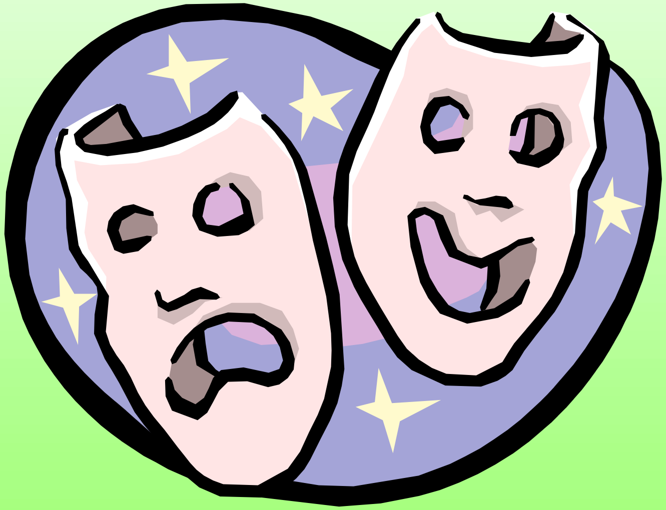
While the **latter** are primarily **knowledge-driven**, the **former** are primarily **data-driven**.

While **bottom-up approaches** are of a **deductive** nature **analysing sub-systems in a detailed way**, **top-down approaches** are of an **inductive** nature **analysing whole systems in a global way**.

The **strengths of top-down approaches** lie in their **potential to unravel inter-relationships between sub-systems thereby uncovering 'missing links' and 'key players'**. They **provide hypotheses** based on the analysed data which are then **to be tested experimentally** and fed back **to improve bottom-up modelling** in Systems Biology.

The Play

NiMOC Act so far and ongoing



NiMOC – The Play so far

- **NiMOC Focus Group established** during the NiSIS Kick-off Meeting in Aachen, Germany, **04-05 March 2005**; with a talk by the NiMOC Member BCJ (M. Pfaff) on potential cross-activities with the industry-driven EUREKA Cluster 'InSysBio – Integrative Systems Biology'; NiMOC activities planned for 2005; elements of a NiMOC Roadmap Contribution identified by an **initial brainstorming**.

- **Student Exchange**: A PhD student (T. Scharl) from the NiMOC Member BOKU Vienna (K. Bayer) visited the NiMOC Member HKI (R. Guthke) **14-15 March 2005**; methods for the analysis of gene expression data from recombinant *Escherichia coli* were discussed.

- **Student Exchange**: A Diploma student (G. Hollanders) from the NiMOC Member University of Maastricht (R. Westra) visited the NiMOC Member HKI (R. Guthke) **22-28 May 2005**; a high-dimensional time series data set from the transcriptome of baker's yeast was analysed by two alternative reverse engineering methods (Westra et al., Guthke et al.) to reconstruct network models (case study).

- **NiMOC Roadmap Contribution written in 2005** (mainly by the NiMOC Member BCJ); first version submitted to the ITB in June 2005; revised version discussed at the NiMOC Meeting held during the NiSIS Symposium 2005 in Albufeira, Portugal; two sessions there on 4 October 2005 with NiMOC activities planned for 2006; NiMOC Roadmap Contribution **finally submitted in January 2006**.

NiMOC – The Play so far

- **Spring School and Workshop on 'Reverse Engineering in Systems Biology'** held in Jena, Germany, **09-10 June 2005**; organised by the NiMOC Members BCJ (M. Pfaff) and HKI (R. Guthke); Spring School in collaboration with TTE; with contributions from NiMOC Members; 35-40 international participants in each event.

- **NiSIS Symposium** in Albufeira, Portugal, **04-05 October 2005**: the following **NiMOC Members contributed accepted papers**: K. Bayer, J. Borges, R. Guthke, T. Mendonca, M. Pfaff, R. Westra.

- **Two Task Forces proposed** by the NiMOC Members BOKU Vienna (K. Bayer) 'Nature-inspired Monitoring and Control' and Degussa (R. Dudda) 'Nature-inspired Industrial Self-healing Sensors' **and approved** by the ITB **commenced** activities by **01 October 2005**.

- **A further Task Force** on 'Nature-inspired Robustness' **proposed** in co-operation with the NiN Member Goethe University Frankfurt (R. Brause) **and approved** by the ITB for **2006-2007**.

- **Survey on Nature-inspired Modelling, Optimisation and Control** by the NiMOC Member BCJ, **written in 2005 and submitted in January 2006**.

NiMOC – The Play so far

- **Spring School and Workshop on ‘Top-down Approaches in Systems Biology’** held in Jena, Germany, **04-05 May 2006**; organised by the NiMOC Members BCJ (M. Pfaff) and HKI (R. Guthke); with contributions from NiMOC Members; more than 35 international participants in each event.

- **NiMOC Workshop on ‘Knowledge Discovery and Emergent Complexity in Bioinformatics’,** held in Gent, Belgium, **11 May 2006**; organised by the NiMOC Member University of Maastricht (R. Westra).

- **Edition of a special issue of ‘Lecture Notes in Bioinformatics’** in relation to the NiMOC Workshop in Gent is under way; edited by the NiMOC Member R. Westra; with contributions from other NiMOC Members.

- **NiMOC Members** R. Westra (Co-ordinator), D. Linkens, M. Pfaff and R. Guthke together with other scientists from Europe **submitted a STREP Proposal** in **September 2005** with the title **‘XECONINE - eXploring Emergent COmplexity in Natural Information NEtworks‘**.

- **NiMOC Members** K. Bayer, R. Guthke and R. Westra together with other scientists from European countries **submitted a proposal** within the transnational initiative **‘Systems Biology of Micro-organisms’**.

NiMOC – The Play goes on

2006:

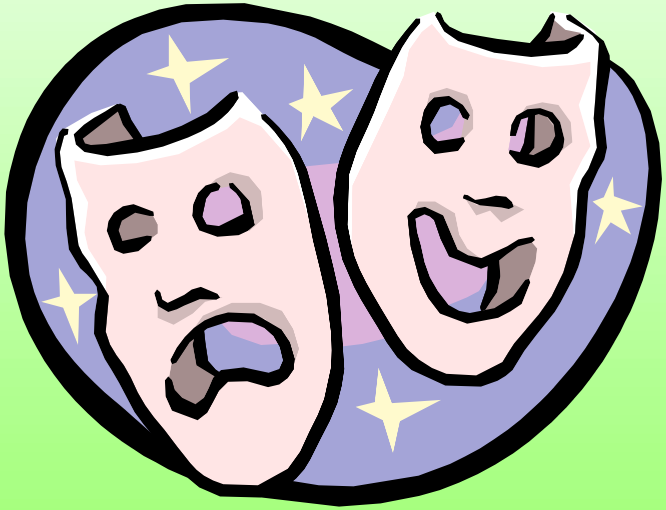
- **NiSIS Brainstorming Meeting**, Palma de Mallorca, Spain, **08-09 June 2006**; with NiMOC Sessions and contributions from the NiMOC Members J. Borges, R. Guthke, C. Hummert, K. Leiviskä, T. Mendonca, M. Pfaff, R. Westra, S. Zellmer.
- **Special NiMOC Session at the CONTROLO Conference** in Lisbon, Portugal, **September 2006**; organised by the NiMOC Members J. Borges and T. Mendonca.
- **NiSIS Symposium**, Tenerife, Spain, **November 2006**; with NiMOC Sessions and contributions from NiMOC Members.

2007:

…

The Future Play

Quo vadis NiMOC?
Can the Evolutionary View be helpful?



Brainstorming in Dialogue with a Star Guest from the Past:

Charles Darwin

by original quotes from

THE ORIGIN OF SPECIES
BY MEANS OF NATURAL SELECTION

London, John Murray, 1859

Darwin‘s Book

THE ORIGIN OF SPECIES
BY MEANS OF NATURAL SELECTION

represents the Theory of Evolution.

Surprisingly the term ‘Evolution‘ does not appear
in Darwin‘s Book.

C.D.: ... can we doubt (remembering that many more individuals are born than can possibly survive) that individuals having any **advantage**, however slight, over others, would have the best chance of **surviving** and of procreating their kind? On the other hand, we may feel sure that any variation in the least degree injurious would be rigidly destroyed. This preservation of favourable variations and the rejection of injurious variations, I call **Natural Selection**.
CHAP. IV. NATURAL SELECTION. 81

C.D.: By my theory these allied species have descended from a common parent; and during the **process of modification**, each has become **adapted to the conditions of life** of its own region, and has supplanted and exterminated its original parent and all the transitional varieties between its past and present states.
CHAP. VI. TRANSITIONAL VARIETIES. 173

C.D.: If we look to long enough intervals of time, geology plainly declares that all **species** have changed; and they have changed in the manner which my theory requires, for they **have changed slowly and in a graduated manner**.
CHAP. XIV. RECAPITULATION. 465

C.D.: Under **domestication** we see much **variability**. This seems to be mainly due to the **reproductive system** being eminently susceptible to changes in the conditions of life; so that this system, when not rendered impotent, **fails to reproduce offspring exactly like the parent-form**. **Variability is governed by many complex laws**, by correlation of growth, by use and disuse, and by the direct action of the physical conditions of life.
CHAP. XIV. RECAPITULATION. 467

C.D.: **Man does not actually produce variability**; he only unintentionally **exposes organic beings to new conditions of life**, and then **nature** acts on the organisation, and **causes variability**. But **man** can and **does select the variations** given to him by nature, and thus accumulates them in any desired manner. He thus **adapts** animals and plants **for his own benefit** or pleasure.
CHAP. XIV. RECAPITULATION. 467

NiSIS/NiMOC:

How can a Nature-inspired Smart Information System achieve predefined or desired function and behaviour?

An answer is: by Modelling, Optimisation and Control, more precisely **by *Evolutionary* Modelling, Simulation, Optimisation and Control**. What does this mean?

Modelling, Simulation, Optimisation and Control mark **essential steps in the design of Nature-inspired Smart Information Systems** with predefined properties.

In view of lacking knowledge about information processing as well as about structure-function relation or genotype-phenotype relation of the living system, **such a design can not be done at once**.

Rather, **it will require many repeated attempts of model modification**, subsequent simulation runs to check the model behaviour, optimisation to adjust model parameters or even model modules in order to correct the behaviour, and control to guarantee the stability of the behaviour.

NiSIS/NiMOC:

This design has very much the character of a **trial and error procedure** whose convergence is not certain but can be achieved by operating as carefully and systematically as possible by drawing the right conclusions from both successful and failed attempts.

The **repeated attempts** of model modification **generate** a whole **quasi-population of model mutants** evolving under the selection pressure to achieve the predefined function of the Nature-inspired Smart Information System. During the design process those **mutants that show desired properties** or come close **will propagate fastest and therefore survive** whereas failing model mutants will die out.

NiSIS/NiMOC:

Inspiration from Nature means to understand the **analogy or metaphor** between **evolutionary preparation** and **evolutionary design**:

- The device for evolutionary preparation is replaced by the designer's lab.
- Mutations are replaced by model variants (genotype, structure).
- Selection of species function is replaced by selection of simulation behaviour (phenotype, function).
- Food resources are replaced by the designer's ideas.
- Selection pressure is replaced by limited computer and other resources.
- The experimental procedure is replaced by computer experiments.
- Finally, evolutionary preparation is replaced by evolutionary design through Modelling, Simulation, Optimisation and Control.

NiSIS/NiMOC:

Analogy to Evolution

- not only important with respect to the general methodology,
- but also with respect to specific methods and algorithms.

Current and future **Nature-inspired Modelling, Optimisation and Control Algorithms** are or will be **evolutionary, developmental, adaptive, self-learning, genetic, genomic, transcriptomic, proteomic, metabolic etc.** taking their **blueprints from Nature's Strategies** that render living systems **flexible, robust, fault-tolerant, noise-resistant, adaptive and evolvable**.

They are or will be related to disciplines like:

- **Artificial Intelligence**
- **Swarm Intelligence**
- **Ants Intelligence**
- **Bees Intelligence**
- **Agent Intelligence**
- **Immune Intelligence**
- **Biotope Intelligence**
- **Ecology Intelligence**
- **Economy Intelligence**
- **Artificial Life**
- **Neuroinformatics**
- **Socioinformatics**
- **Computational Biology**
- **DNA & Molecular Computing**
- **and many others**

The Challenges

Existing Nature-inspired Methods for Modelling, Simulation, Optimisation and Control are **already quite numerous but scattered and isolated**.

Needed is their integration into some repository, arsenal or platform where they are available from for flexible incorporation into the strategic pipeline of Systems Modelling, Simulation, Optimisation and Control.

Real-world applications outside the academic domain still **seem to be rare**. However, it is here that theory has to be proven finally.

The Grand Challenge

Future work in the field of Nature-inspired Smart Information Systems must furnish the **transition from recovering Nature's principles to using this knowledge for the design of advanced information systems**.

This transition is often called the transition **from Systems Biology to Synthetic Biology** (or Constructive Biology).

Referring to Kitano‘s Notion of Systems Biology

and its research fields of importance

- Genomics and Related Molecular Biology
- Simulation, Bioinformatics, Software Development
- Analysis of Dynamic Systems
- High Technology for Reliable Measurements

and in particular its tasks

- System Structure Identification
- System Behaviour Analysis
- System Control
- System Design

the following Vision for NiSIS arises:

The Vision

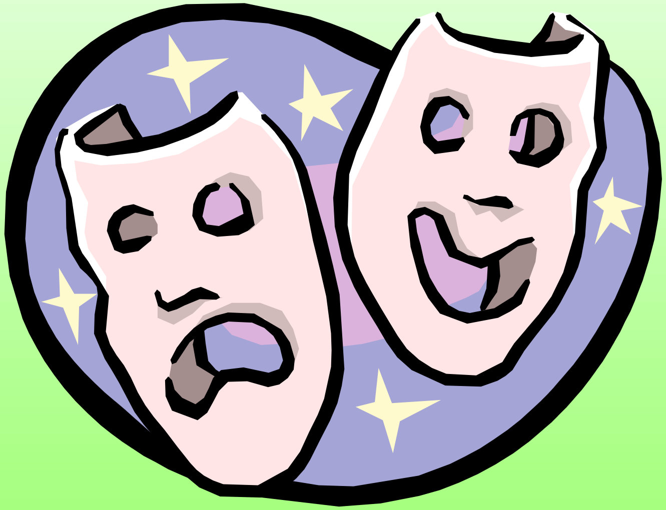
In terms of ***structure***, standard ideas of aggregation and decomposition in engineering science must be replaced by flexible decentralised paradigms. Reconfigurable structures are required in order to attend to the needs of self-repair/self-healing.

In terms of ***function***, the well-known engineering design cycle must change from ist sequential specification to self-goal-specification under constraints and competition, from planning to self-forecasting, from design to rule-driven self-organisation, from analysis to self-understanding, from implementation to self-realisation, from observation to self-monitoring, and from control to self-decision-making (autonomy).

In terms of ***behaviour***, fixed parameter models have to be replaced by those that can even adapt their modularity. Behaviour itself will change from monotypical predictable modes to those which are multitypical, competitive, collaborative, cooperative, deceptive, and to goal-driven forms of behaviour. Self-aware IT networks will be required, capable of automatic reconfiguration of their topology, and self-organising information repositories for data sets and model modules. The ultimate aim is for self-designing and self-maintaining software IT systems.

The Play

... is over for today ...



Thank you very much indeed for your attention!