NTNU

Norwegian University of Science and Technology

Lecture 8

EvoDevo

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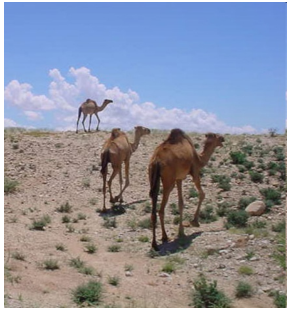
Contents

Scalability In EAs?

- Complex problems:
  - Tune representation
  - Tune GA: operators, selection method....
  - Divide and Conquer
  - Incremental Evolution

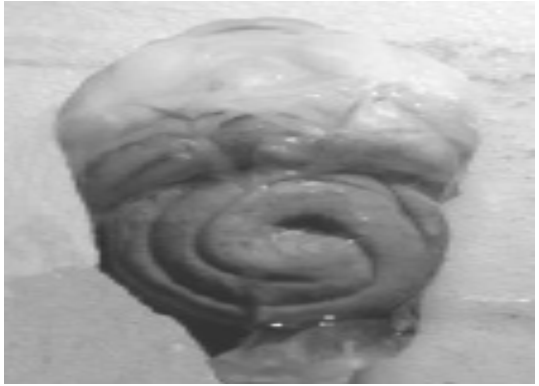
Look to biology: Development process

What about Adaptivity?


- An Organism Develops in an Environment
  - Phenotype adapts to THE environment
- An Organism Functions in a potentially changing environment
  - Phenotype adapts to changes in the environment

Function and Structural Adaption



- Environment change
  - Less food

→ Physical change

→ Functional change

  - Plant eater to carnevour
    - Canibalism
- Stable environment
  - Reversed process

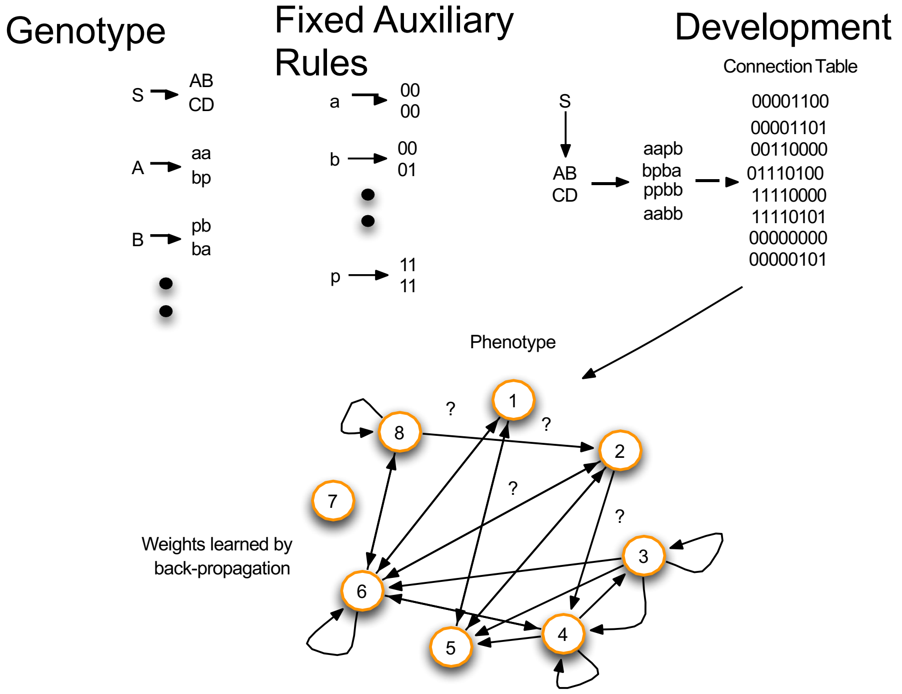
POE System

- **Phylogenetic** or Evolutionary
  - genetic operators, fitness functions, etc.

- **Ontogenetic** or Developmental
  - non-trivial genotype-to-phenotype mapping.
  - genotype is a *recipe* that, through some recursive growth process, produces the phenotype.

- **Epigenetic** or Learning
  - During actual performance testing
  - system is able to modify itself in some manner that effects future behavior.

A Classic Early Developmental Encoding



Kitano's (1990) encoding of ANNs as context-free grammars.

The first complete POE system

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Biological Development

Development is essentially the emergence of organised structures from an initially very simple group of cells

- Evolution *designs* life
- Development *builds* it
  - construction and self-organisation
  - interplay of proteins, genes, cells, and environment
  - **life time proces**s

Single Cell to Multicellular Organism

- cleavage division (no increase in cellular mass)
- pattern formation
  - initial body plan - coordinate system
  - germ layers - ectoderm, mesoderm and endoderm
- morphogenesis
- cellular differentiation
  - cell signalling
  - asymmetric division
- growth (cellular proliferation, cell size)

Mechanisms: Proteins

- specify cell behaviour
- acts as an enzyme - catalyst
- unique sequence of amino acids –
  - distinct 3D form determined by ordered nucleotides in genes
  - codon = nucleotide triplet = distinct amino acid
- Transcription factors

Gene Regulatory Network (GRN)

- **Cell**: Protein processing machine

- Set of genes, proteins, small molecules
  - **Genes** encode proteins
  - **Proteins** control cell function
  - DNA -> RNA -> proteins
    - Each step, self regulation of the cells function
    - Adjust amount/type proteins produced
      - Protein thresholds for cell function activation

GRN: Network of Genes

- Nodes are **genes**

- Input: **transcription factors (proteins)**

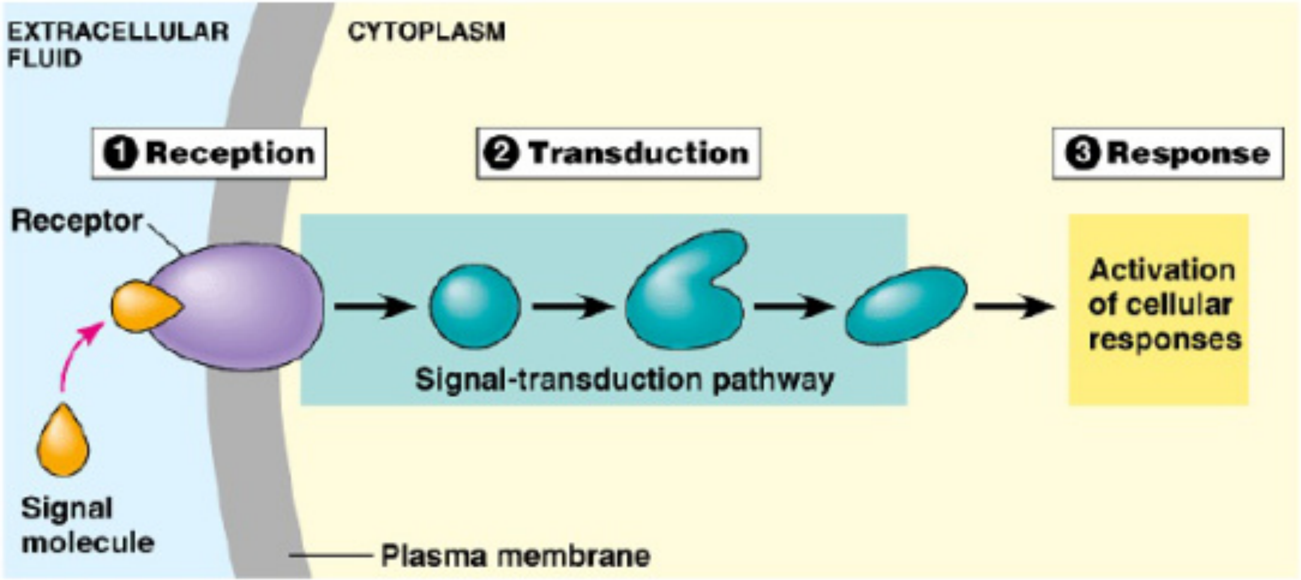
- Output**: Gene expression**
  - Cell response
  - Expressed gene = active gene (turned on)

- Unicellular organisms
  - Respond to external environment to make cell survive
- Multicellular organisms
  - Control transcription, cell signalling and development

Signalling Pathways and Transcription Factors

- **Signal**
  - Incoming molecule to the cell, input to GRN
- **Signalling pathways**
  - Respond to signals
  - Response: cascade of biochemical reactions
    - Leads to one or more cellulær activities
      - Gene regulation (on/off specific genes)
      - Protein activity (opening/closing ion channel)
      - Change in cell metabolism (breakdown of glcogen)
- **Transcription factors**
  - Proteins that convert DNA to mRNA
  - translation: mRNA -> protein)
  - Bind to genes

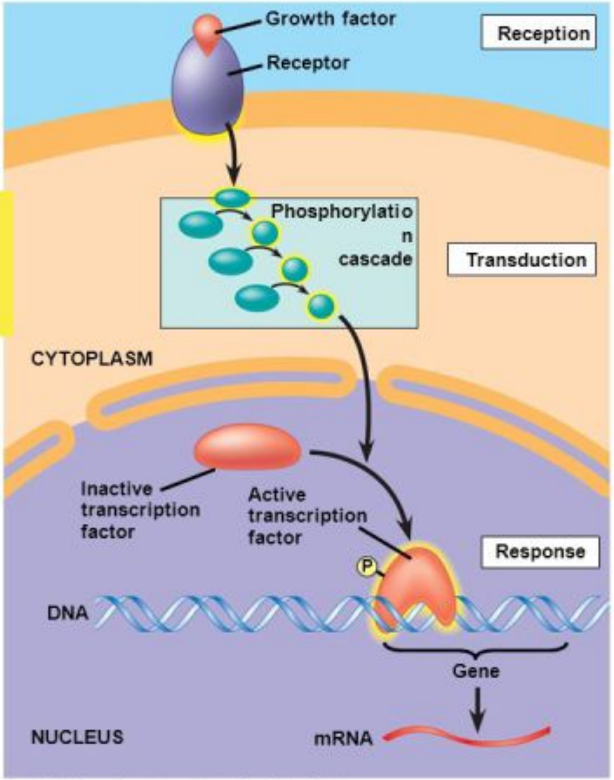
Three Stages of Signal Transduction



Regulating Gene Expression

Fig. 11-14

Modulating Gene Activity



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Artificial Development

- Model biological Development

- Artificial Development : computation technique
  - complex designs
    - Naturally avoids 1 → 1 - compact genotypes
  - naturally exploits : symmetry and modular structures
  - scalable, self-organised and distributed process
  - robustness - adaptivity to environment

Synthesis of Development Systems

- By Hand:
  - The rules are given
  - Can ”easily” be deduced e.g. Moss leaves
  - Geometric specifications are not strict e.g. plant-like
- Search:
  - non trivial developmental outcome
    - neural network robot controller, electronic circuit
- Inverse problem: finding the development process
  - Too challenging

Evolution automates the synthesis of developmental systems and the developmental representation provides a

more evolvable and more powerful evolutionary process

Evolution + Development = EvoDevo

Artificial Development

- Problem description = DNA (genome)

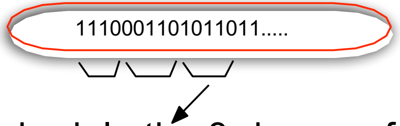
- Development Process

  – DNA decompressed(unfolded) into a potential solution
    - Complex process of gene regulation
    - Simpler developmental process

  – Single cell to multicellular organisms through the actions of cells

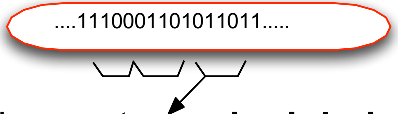
Genotypic Encodings : DNA

- **Direct**
  - Position (in chromosome) and bits determine a phenotypic trait, independent of all other genes.



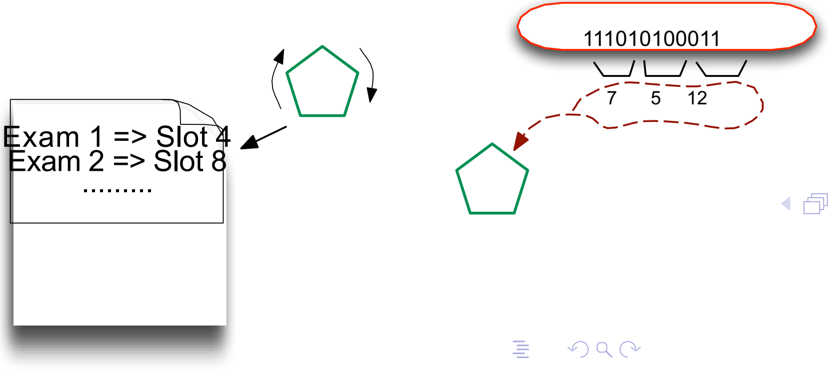
Schedule the 3rd exam for the 10th time slot.

- **Indirect (uncompressed)**
  - Genes may interact in determining traits.
  - Chromosomal position and/or bits may only be relative indicators.



Schedule the **next unscheduled** exam for the 10th of the **unfilled** time slots

- **Generative (developmental)**
  - Genes encode parameters for a developmental scheme.



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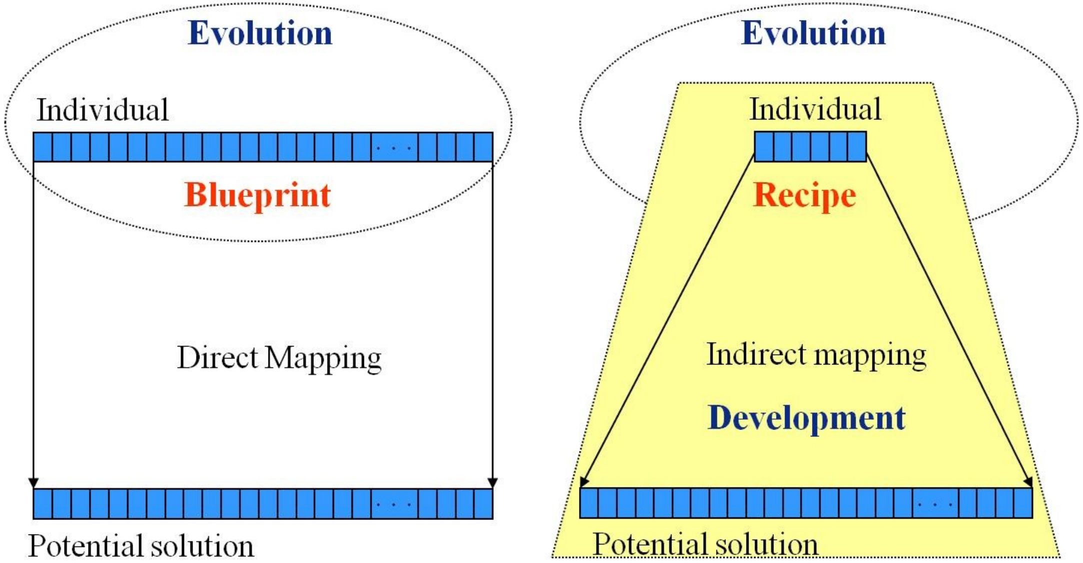
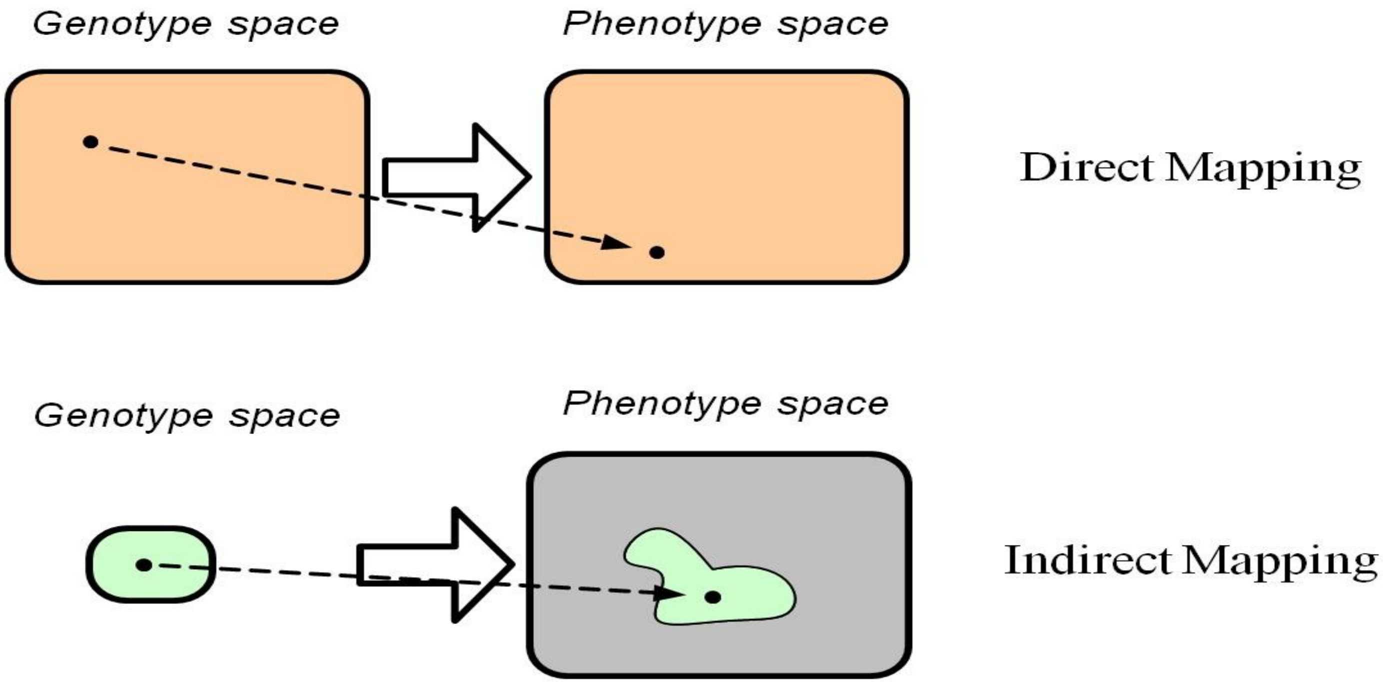
Evolving 'DNA'



Goal: Simpler genotype, more efficient evolution

Challenge: Complexity is in the mapping!

Challenge: Finding the Right DNA

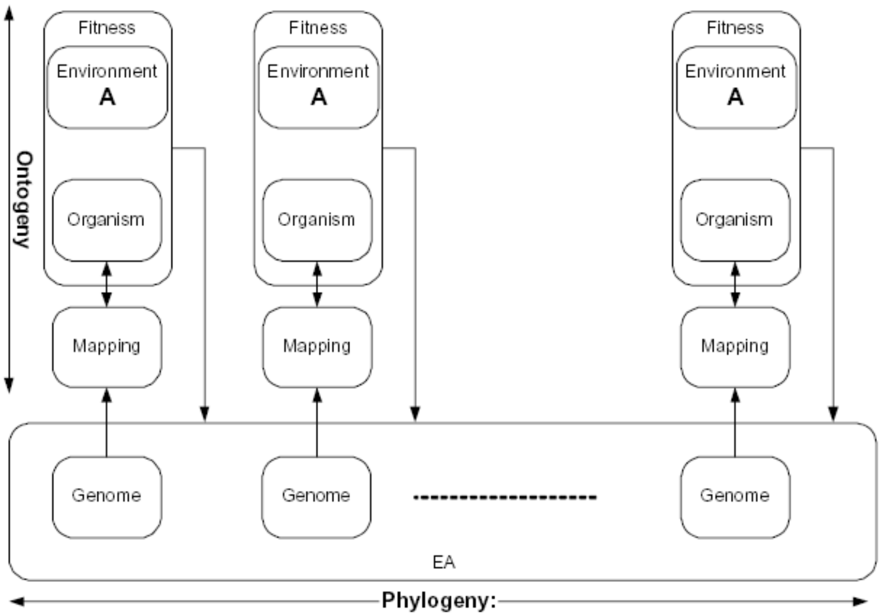


Phenotype space = 2^Length of phenotype:

Developmental Representations

- Advantages
  - Complex phenotypes generated from compact genotypes.
  - More biologically realistic
  - Facilitate evolution of repetitive structure.
  - Can support gradual evolution of complexity.
- Disadvantages
  - May overconstrain search
  - Difficulty finding needle in a haystack optimal solutions.

Challenge: Adaptive Solution



Fixed environment A

Adaptive solution, A and B?

- Test each solution in both environments

Unknown environment?

Challenge: Fitness?

- DNA + development process
- Fitness says little about DNA itself
  - Indirect evaluation of DNA
- What if the evolved developed phenotype does not resemble the organism
  - Need some way of ‘goodness*
- How good is the development path chosen?

Fitness should measure the developmental process as well as the result......

Challenge: Bio-plausible Vs Bio-inspired models

- Bio-Plausible:
  - support biological research
  - mechanisms at work and interplay
  - more realistic artificial model for computation
    - disadvantages:
      - resource greedy
      - is such a complicated process needed?
      - will natural development solve artificial problems
- Bio-inspired:
  - Artificial goal
  - Need effective process

Contents

Which Development Model?

- Use someone's favourite model?
  - Not understood
  - Wrong starting point?
  - Normal for a maturer research field / popular
- Start from scratch?
  - Normal early in a research field
- **We are still far from understanding**
  - what a development model is
  - how it should be applied
  - what such a model might achieve

Model 1: L-systems

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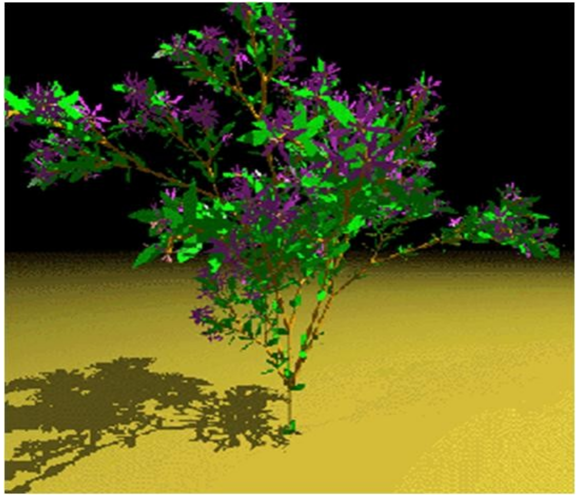
L-systems

Introduced as a rewriting system to model organism development.
Represent a powerful formalism to model plant development [Lindenmeyer, 1968]



L-system : rule based system

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L-system
- Alphabet **A**: a set of symbols
- An axiom **w** (initial string of symbols)
- set **P** of production rules
- stopping condition OR self-limited growth

- Production Rules:
  - predecessor → successor
  - applied in parallel
  - recursively replace all symbols in the string
  - identity production rule, p_0; $s \to s$.
    - Assumed if not other specified

Simple example

A: abc

W: a

P: $a \to abc$

$a \to abc \to abcbc \to abcbcbc$....

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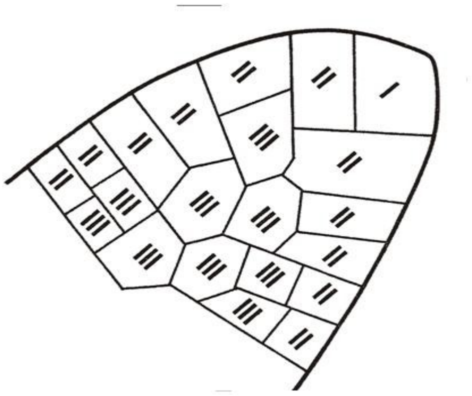
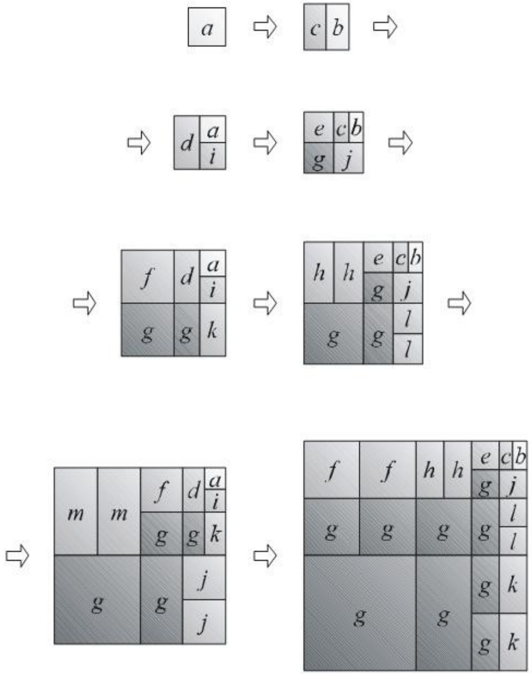
L-system: Biology Modelling

Development of a Moss Leaf [Lindenmayer 1975]





$$A = \{a, b, c, \ldots D, R\}$$

$$\omega = a$$

$$p_1 = a \rightarrow c\,R\,b$$

$$p_2 = b \rightarrow a\,D\,i$$

$$p_3 = c \rightarrow d$$

$$p_4 = e \rightarrow f$$

$$\ldots$$

$$p_{13} = m \rightarrow f\,D\,g$$

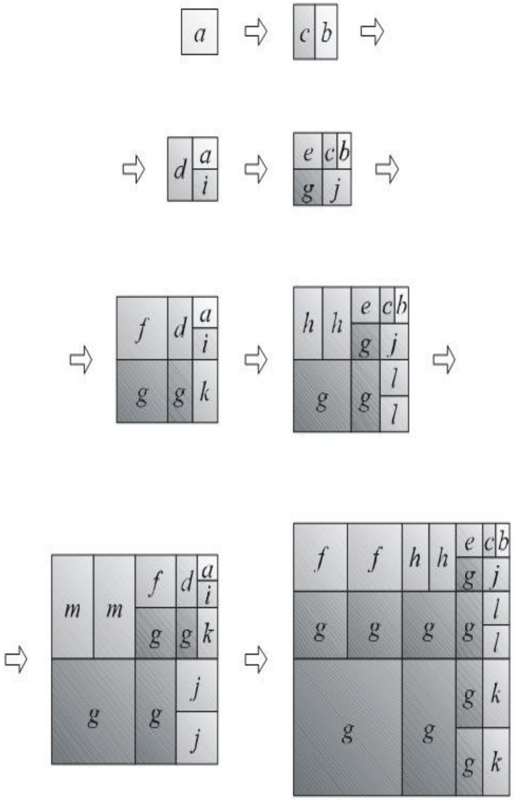
Primary cells	I
Secondary Cells	II
Tertiary Cells	III

Production Rule Effects

- **Cell division**
- **Cell type change**
- **Cell growth (mass)**

Grow Rules

- Increase cell Mass or
- duplication



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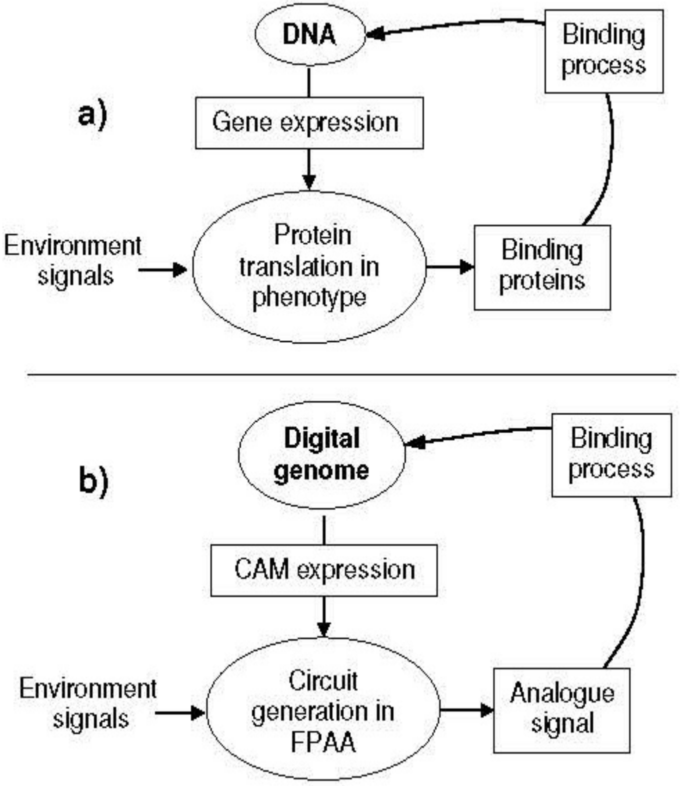
Application to Computer Graphics

http://gug.sunsite.dk/

http://www.ii.uib.no/~knute

http://www.uweb.ucsb.edu/~svetlin

Model 2 GRN: analogue electronics



[Kester Klegg, PhD thesis, York UK]

Biology Concept

- Environment Signal (protein...)
- Protein binding

→ activates genes

→ gene expression

Analogue Electronic Concept

- Input signal = Env. Signal
- input → output (translation)
- output → ‘protein’ mask
- Gene = CAM, Configurable Analogue Module

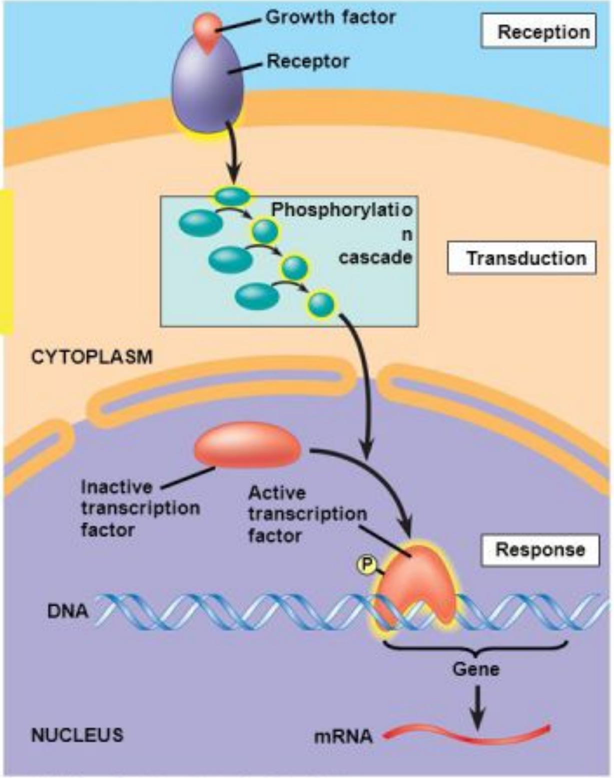
→ activates genes

→ CAM expression

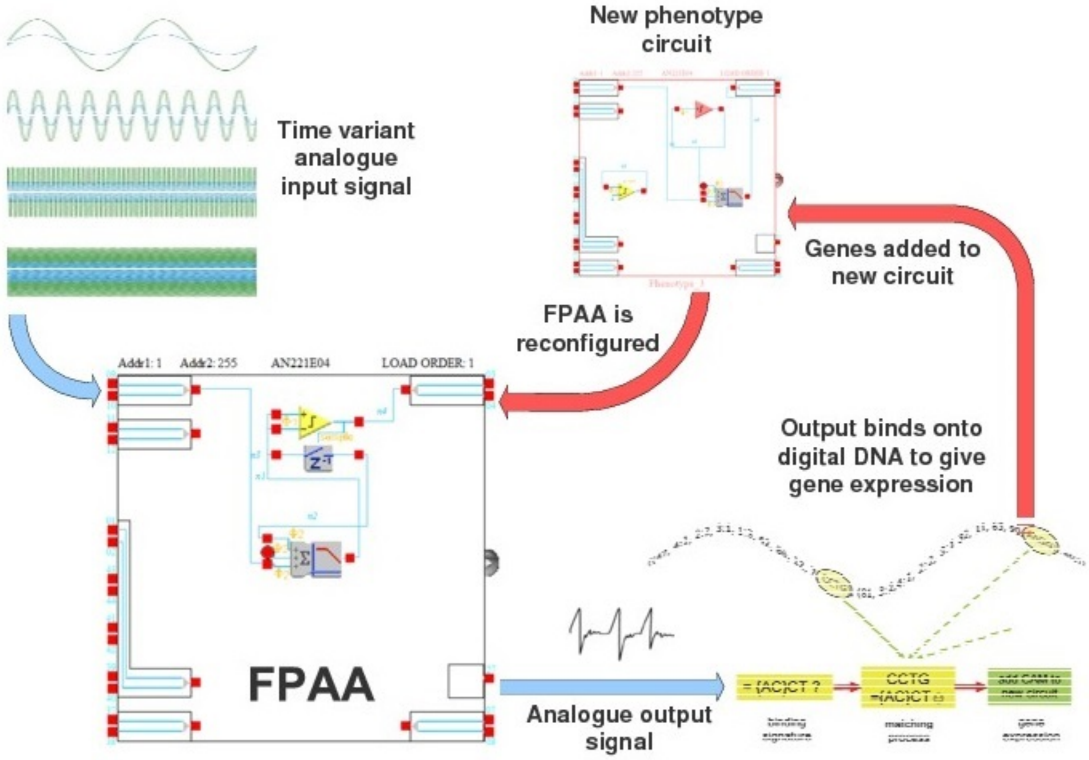
Regulating Gene Expression

Fig. 11-14

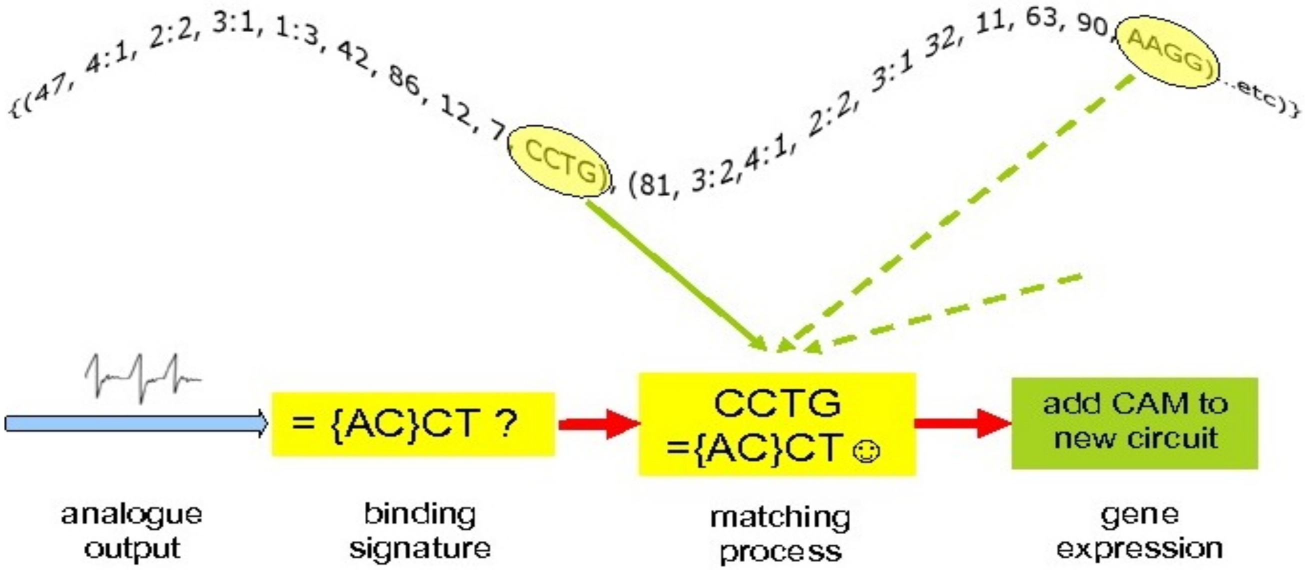
Modulating Gene Activity



GRN example: Analogue Circuit



GRN: CAM expression



Model 3: Simple GRN Model

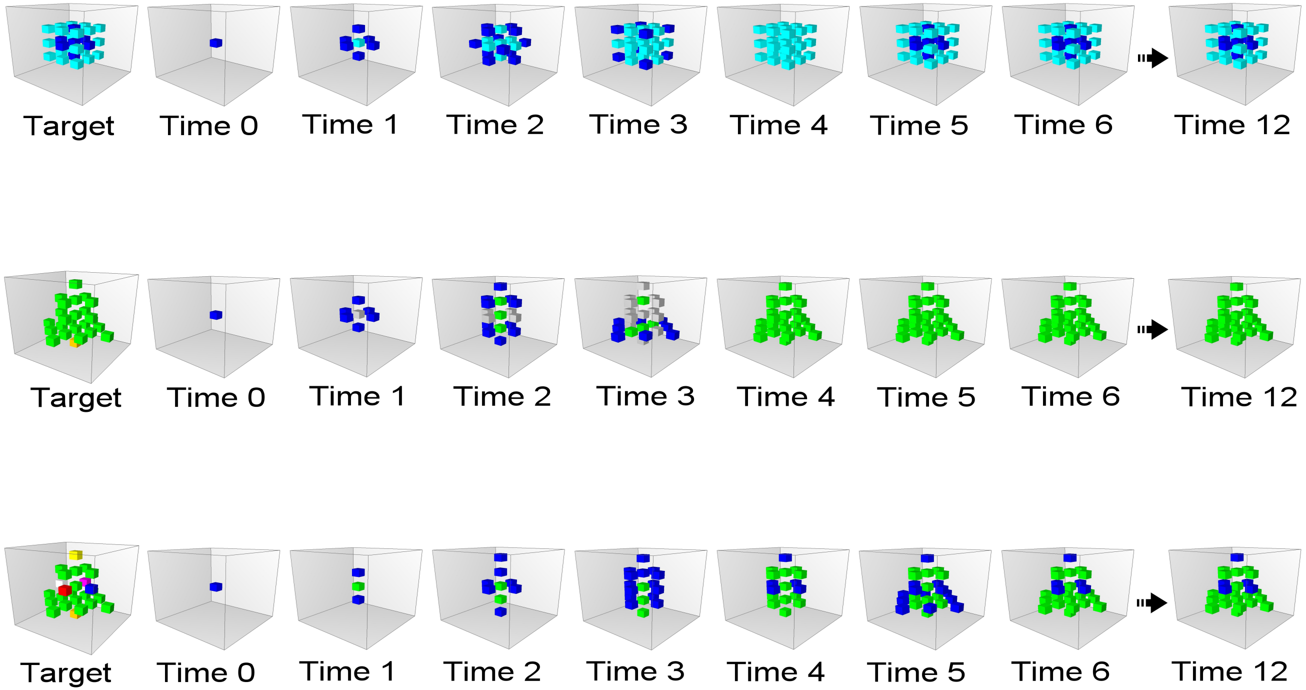
- Masters work Johan Høye, EVODEVO
- 3D structures

- Features:
  - Cell with DNA, chemicals, proteins
  - 6 neighbours
  - Set of rules for updates
    - Evolution refines the rules

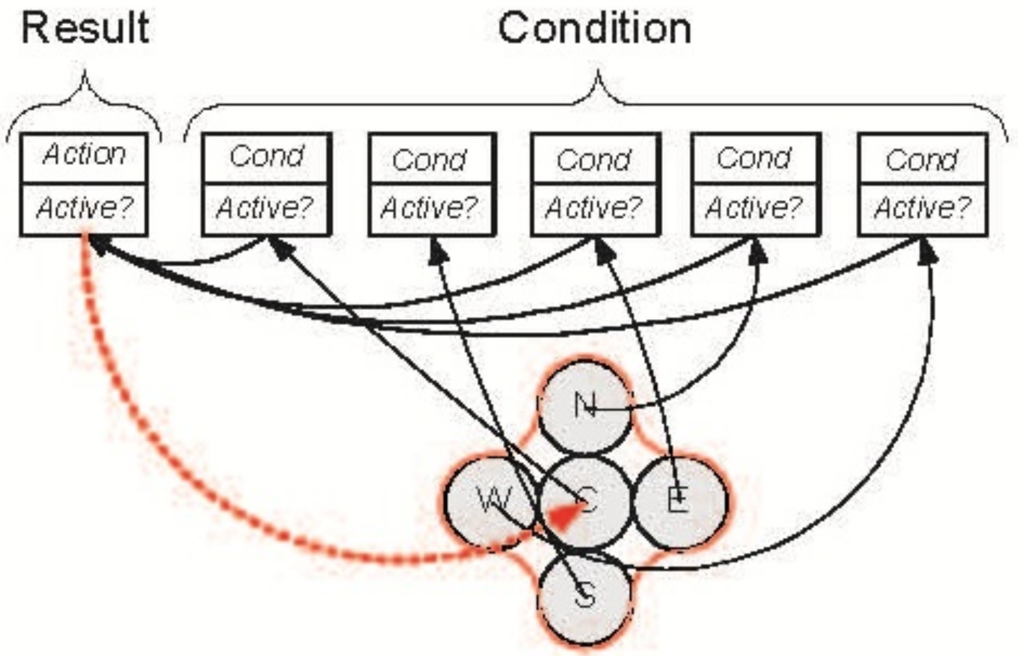
- Single cell to multicellular organism
  - Static structures
    - Growth (replication)
    - Change (new function – colour)

Artificial Development of 3D shapes

When developing shapes(forms), achieving irregularities and asymmetries can be challenging.

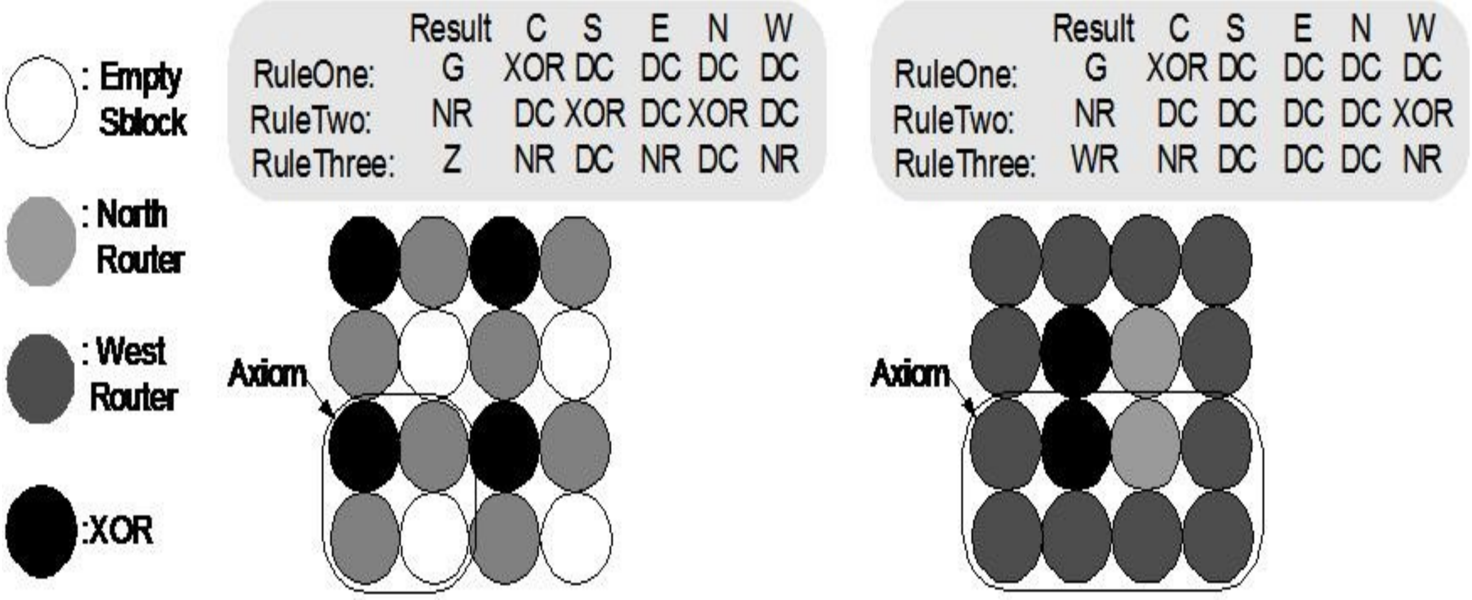


Model 4: Rule–based system



2D cellulær automata

Achieving Patterns



	Result	C	S	E	N	W
RuleOne:	G	XOR	DC	DC	DC	DC
RuleTwo:	NR	DC	XOR	DC	XOR	DC
RuleThree:	Z	NR	DC	NR	DC	NR

a: Repeated pattern

	Result	C	S	E	N	W
RuleOne:	G	XOR	DC	DC	DC	DC
RuleTwo:	NR	DC	DC	DC	DC	XOR
RuleThree:	WR	NR	DC	DC	DC	NR

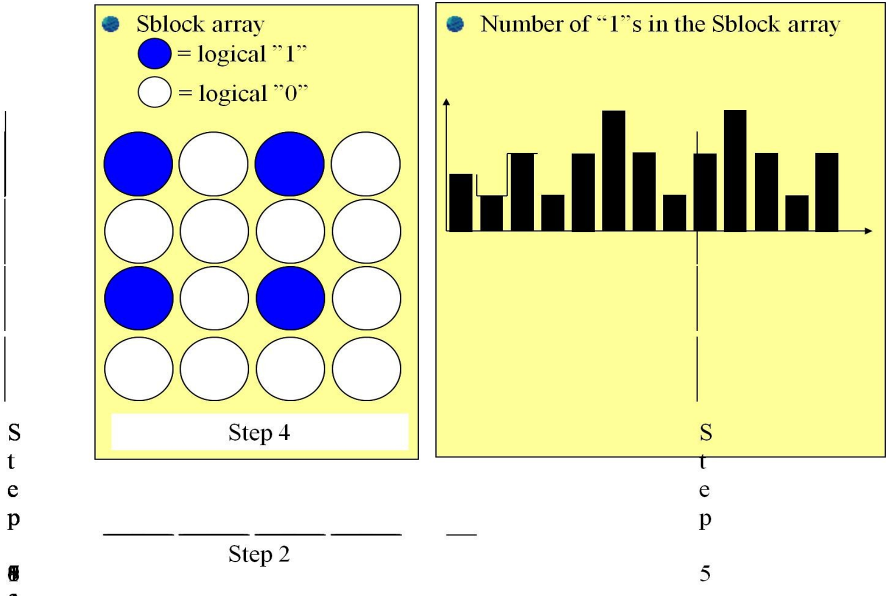
b: Symetrical pattern

Development Time

- Achieving structures
  - **Development step**
    - Single update/application of the development rules
    - Create new cells, change type of cells..... Based on rules

- Achieving function
  - Development step
  - **State Step**
    - Function updates across cells
    - Cell function (value) depends on state of neighbours
    - Changes in state neighbour -> state update (next clock)

Achieving Functionality



Grid is the developed organism

- each cell has
  - a type
  - a value @ time *t*

Function = entire organism

- **interpretation** of state patterns
- cyclic patterns over time
  - 4 step pattern

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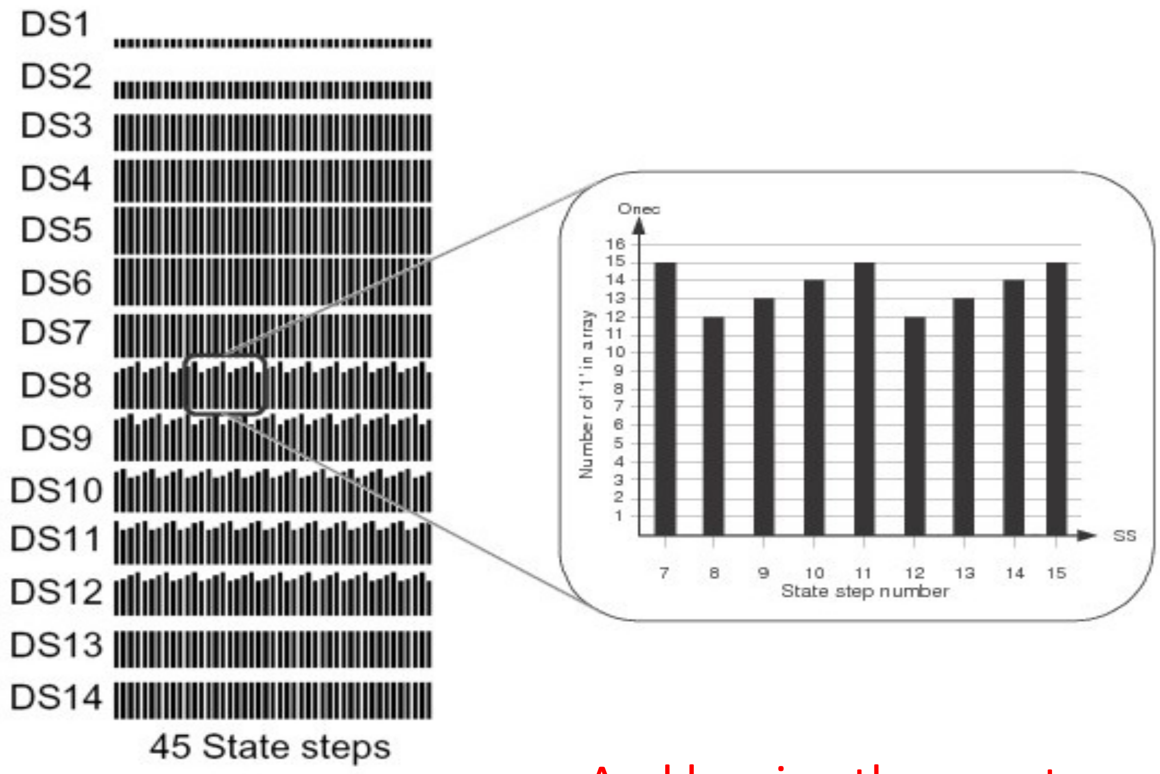
CA model: Achieving a 4-step counter



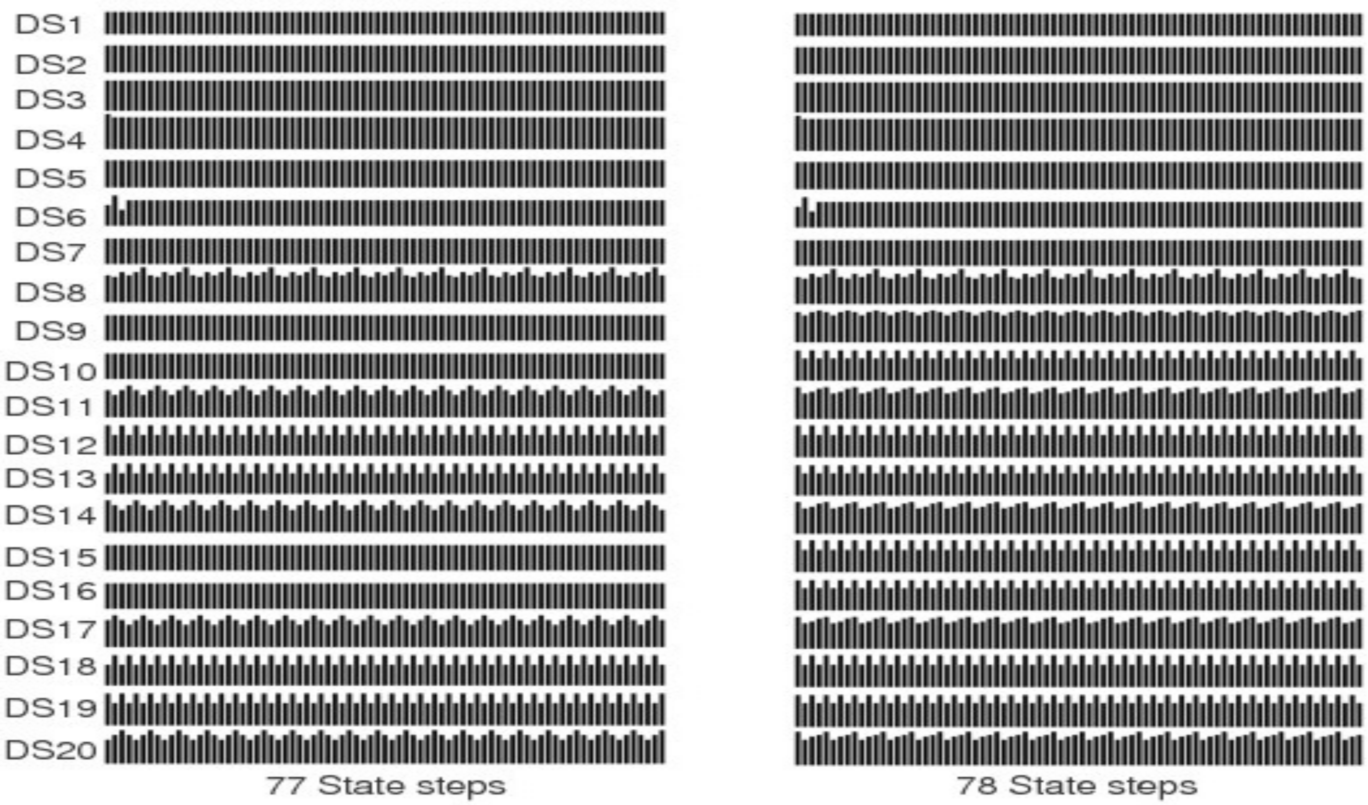
And loosing the counter...see DS 13!

Challenges : When to stop?

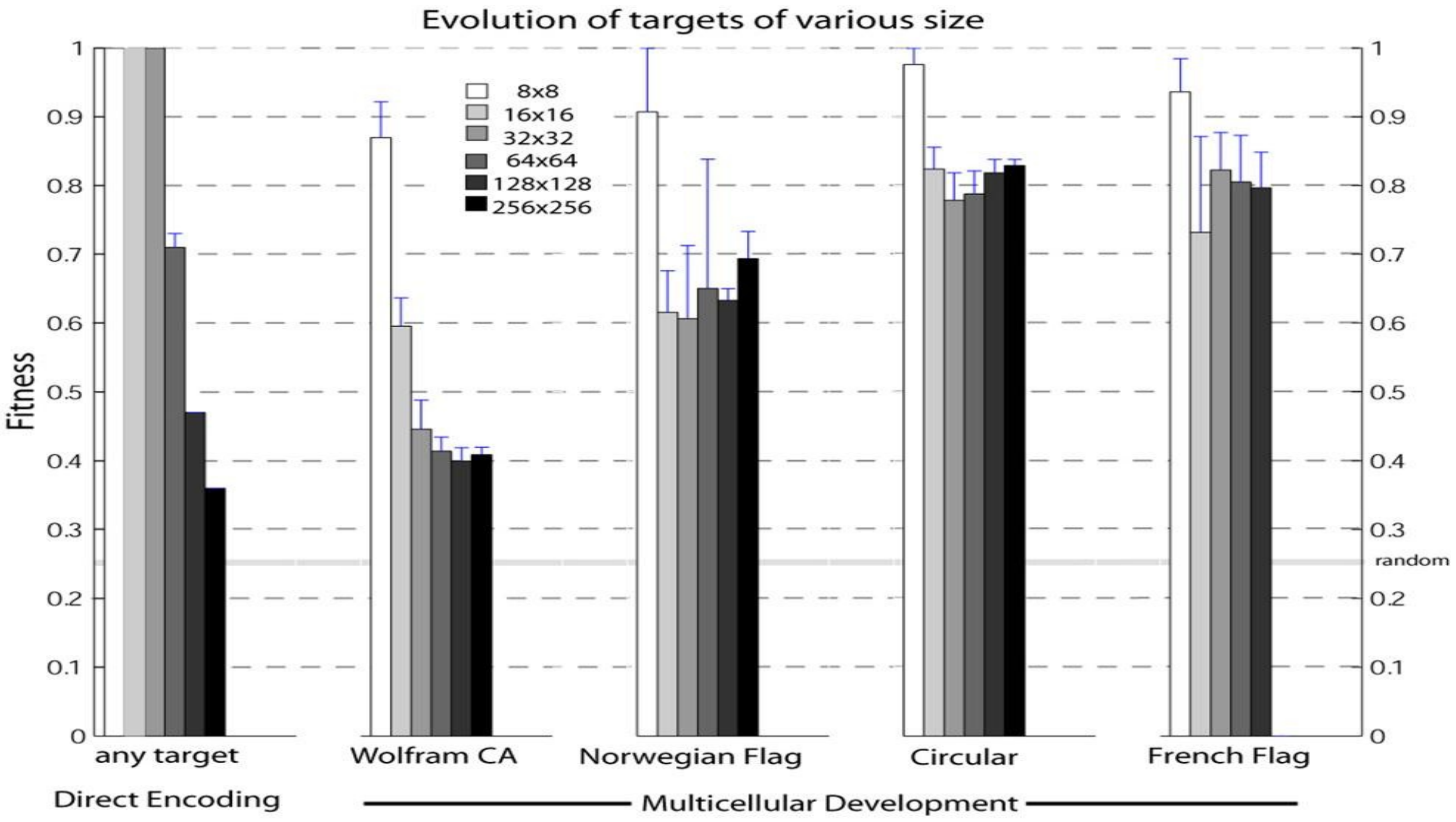
- EvoDevo:
  - Developing the phenotype for an individual (during evolution)
    - Fitness evaluation

- When to stop development?
  - How many development steps?
    - Example: counter dissappeared...stop earlier?
    - do you want to stop or just stabilise?
    - Adaptive solution needs to re-develop
  - How many state steps?

Challenge: ripple effect: when to stop?



Scalability?



Scalability

- increase in solution size – scalable?
  - Example: Kozas evolved (GP) analogue solutions
    - Huge resources to create highly complex circuits
    - Good for one-off solutions
    - Efficient scalable technique?

*Scaling up of problem size **without** a corresponding increase in resource requirements*

Contents

- Introduction :
  - Complexity and Adaptivity
  - POE System
- Biological Development
- EvoDevo
- EvoDevo challenges
- Different Development Models
- Further EvoDevo challenges
- Related Applications

Related Applications : research

- **DNA Tiling**
  - Part of DNA computing
  - biological form of cellulær computation
    - DNA cells
  - Reconfigurable biological technology

- **Self-healing Materials**

Required Reading

- Chapter 2: 2.1-2.4, chapter 4, Floreano book

- Achieving a simple development model for 3D shapes: are chemicals necessary? Pauline haddow and Johan Høye, Proceedings of the 9th annual conference on Genetic and evolutionary computation, 2007

- EVOLUTIONARY SEARCH APPLIED TO RECONFIGURABLE ANALOGUE CONTROL, Kester Clegg, Susan Stepney, Tim Clarke, International Conference on Field Programmable Logic and Applications, 2007. FPL 2007