Individual vs ecosystem based complexity

*evolution predictable???
LAST TIMEs

Metabolism centered models

“real life” examples clarified through evolutionary models (lac operon, ribosomal RNA, causal drift, WGD)

FBA upscaling to full cell (and ecosystem based) models.

HOWEVER: “external environment” externally set (except Lac operon; ecosystem based FBA models)

TODAY

Direct Feedback to and from environment from virtual cell to virtual microbe

Coevolutionary problem solving

TODO based behavior
“Virtual Microbes”
a paradigm system for bottom up modeling of multiple modes of adaptation in biological-like complex complex adaptive systems

Thomas Cuypers and Bram van Dijk

Cell with
Genome with
genes (TFs, pumps, enzymes) with parameters (Vmax, K, binding)
metabolism
grow and divide
Mutate
(duplication/deletions, HGT, par. changes)

In ‘universe’
potential metabolic reactions
Resource influx
space

NO PREDEFINED FITNESS
De Novo evolution in a constant environment (1 resource)

Meijer, v. Dijk & H.
2020
2 types of Evolved metabolism generate predictable ecosystems

“core, shell and cloud”

U-like-shape of pangenome

Cross-feeding ONLY in space!
De Novo Evolution in variable environment

“What” has evolved?, How to observe?

WT 1

WT 2

WT 3

WT n

LCA of evolved population

Harsh, fluctuating environment (2 resources)

Identical for all replicates

van Dijk et al 2019
De Novo Evolution in variable environments

"WHAT" has evolved?, How to observe?

Common metabolic cycle

Harsh, fluctuating environment
Identical for all replicates
De Novo Evolution in variable environments

“What” has evolved?, How to observe?

WT 1

WT 2

WT 3

WT n

ANC

LCA of evolved population

Similar “fitness”

Harsh, fluctuating environment

Identical for all replicates
De Novo Evolution in variable environments

"WHAT" has evolved?, How to observe?

Dissimilar "fitness"

LCA of evolved population

Harsh, fluctuating environment
Identical for all replicates
BUT: very diverse GRN (or none) and metabolic reaction to alternative environments
Experimental evolution:
starting with pre-evolved “wildtypes”

Well known example of experimental evolution:

Long term evolutionary experiment (LTEE) (Lensky 1991)
One strain of E. Coli is evolving in lab-conditions since 1988
(>70000 generations) in 12 replicates
in a serial transfer protocol (diluted in new medium very 24 hours)
still adapting (getting “better”)
Continued new ways of observing & new insights

This case study:

In silico evolution of the above pre-evolved “wildtypes” (WT 1-16)
in similar serial transfer protocol

study “generic” features of such an evolutionary process
  To WHAT does the population adapt?
    HOW does it adapt?
    Multiple observables
  Similarities/differences to E. coli?
In serial transfer protocol they all evolve to “Trust the hand that feeds them” (anticipate 24 hr cycle)

Minimize Lag-phase
Exhaust all food after 24 hours
remaining JUST alive
OR
remaining JUST ready to divide
Maximizing growth rate OR Yield
*evolved* trade-off and distinct strategies
By individual based regulation OR collective tuning
By individual based regulation OR collective tuning
Conclusion

Evolved contingency of predictability
combinatorial set of discrete outcomes

Diversified evolved wildtypes
all evolve anticipation of 24 hr cycle
*un-predicted predictability*

BUT in unpredictable ways

Some WT’s adapt in a predictable way, others in very different ways

*predictability is an unpredicable outcome of evolution*
Conclusions/Observations

- What is fitness / what has evolved not obvious
- Evolutionary attractors can be characterized as a combinatorial set of a limited set of alternatives
- Autonomous and Collective “problem solving” (metabolism) “easy” alternatives
- Non-autonomy not because of lack of genes...
- Spatial embedding, also without spatial patterns important
- Trade-off’s not innate but evolved properties
- GRN very variable (presence and shape)
- Predictability, even in well defined environments depends on prior evolution
  Predictability is an unpredictable outcome of (prior) evolution
Life as “function optimization”
individual vs ecosystem based problem solving

- NON ‘trivial’ task (constructive evolution)
- Problem solving (modeling trick)
- Local vs Global ’fitness’
  sparse fitness evaluation
- Study longterm information integration
- competition and/or cooperation

Spatial pattern formation and speciation enable evolving complex problem solving

Local Competition and Co-evolution as Optimization Strategy (Hillis)

- Evolution of FAST sorter
- Coding:
  Diploid Shuffles
- Fitness:
  # of correctly sorted (side effect)
- FAST SORTERS
Fig. 2. Green's 60-comparison sorter.
Function fitting as model for (complex) TODO
coevolution as optimization strategy
sparse fitness evaluation through co-evolving problems
cf Pagie and Hogeweg 1997, de Boer & Hogeweg 2010, 2012

ISSUES

- How gets the 'complete' problem solved
  - Information integration
  - generalizability (never 'seen' cases)
- What type of solution is generated
  - complexity of solution
  - mutational robustness
  - generalizability
  - individual vs ecosystem based solutions

coevolution host/parasites; predator/prey
compare sparse vs complete fitness evaluation
Individual based problem solving:
Information integration
sparse fitness evaluation more efficient
(< number of evaluations)

Linear model: bitstring match

Target Bitstring
Host: bitstring
Parasite: 3 positions
Fitness host: # correct bit
- at positions of 8 surrounding parasites
Fitness parasites # incorrect bit
- in host atop of it

complete fitness all points
random points
coevolving points
Individual problem solving of harder problem
Type of solution:
complexity, generalizability, mutational robustness

- function: $f = 1/(1 + x^{-4}) + 1/(1 + y^{-4})$
- co-evolved solutions and sampled points in space
- compare sparse fitness evaluation:
  (only some values (8) seen per lifetime) and coevolution
  with 'complete' fitness evaluation (many values seen (here $26^2$))
- fitness distance to target functions

sparse fitness evolution

- better fit (distance)
- "better fit (simpler function)
- "better fit (more generalizable)
- LOWER mutational robustness

Pagie and Hogeweg 1997
Figure 2. Fitness curves of the best-of-generation solution for coevolving (a) and complete static problem evaluation (b). Fitness is based on the complete problem set that consists of 26 x 26 problems. The fitness curves that drop below $10^{-1}$ go to values between $10^{-15}$ and $10^{-17}$. The horizontal dotted lines give the value of the hit criterion (see text).
Looking at solutions

sparse complete sparse complete
on “seen” points on new points

Figure 3. Three typical final solutions produced by coevolving fitness evaluation. The left plots are based on 26 × 26 evaluated problems, the right plots on 100 × 100 evaluated problems. Two correct solutions that approximate the target function are shown in (a) and (b); an incorrect solution is shown in (c). All solutions generalize well on the 100 × 100 problems.

Figure 4. Two typical final solutions produced by static fitness evaluation. The left plots are based on 26 × 26 evaluated problems, the right plots on 100 × 100 evaluated problems. Neither solution is correct.
Spatial pattern formation and PARASITE speciation

\[ G = \frac{1}{1 + x^{-4}} + \frac{1}{1 + y^{-4}} \]

figure 5: parasite speciation in evaluating
Differentiation of host phenotypes:
“good at eating different prey”
individual vs ecosystem based problem solving

Co-evolutionary Problem Solving
LISP style function approximation
Sparse fitness evaluation on a spatial grid

<table>
<thead>
<tr>
<th>Host Parasite</th>
<th>Predator, Prey and Scavenger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance to all parasites</td>
<td>Only best predator feeds on prey</td>
</tr>
<tr>
<td>Fitness defined as distance</td>
<td>Fitness defined as relative distance</td>
</tr>
<tr>
<td>⇒ Individual problem solving</td>
<td>⇒ Ecosystem problem solving</td>
</tr>
</tbody>
</table>

Modify/Extend above co-evolutionary system
3 planes: predator, prey, scavenger
Scavenger “eats left-overs”.

**predator and scavengers do not “see” each other**

succes-rate ecosystem based solution > individual based solutions

problem decomposition
ecosystem based problem solving
speciation of predators, colocalization of predators and scavengers
collective problem solving

Predators + Scavengers

Prey → Eaten Prey

X-solver
Y-solver
Mutant

X-problem
Y-problem
Intermediate
Fully Solved

Y-predator
X-predator

Y-prey
X-prey
Mutation rates and individual based vs ecosystem based solutions

same predator/prey scavenger model

Functions used:

\[ f(x,y) = x^3 + y^3 + 5x^2 \]
\[ f(x,y) = x^3 + y^3 + 5x^2 + xy \]
\[ f(x,y) = x^3 + y^3 + 5x^2 + 2y \]
\[ f(x,y) = y^4 + x^3 + y^3 + yx^2 + y^2 \]

(de Boer & Hogeweg BMC Evol Biol 2010)
high mutation rates lead to ecosystem based solutions (cf hypercycles, RNA model)

evolving information processing

maintaining information processing
Slightly beneficial 'genes' (bits) and individual vs ecosystem based solutions (gene conservation)
Host-Parasite coevolution, above the information threshold
Fitness target: bitstring(256), differential weighted fitness/bit
Wouter Ubbink 2021: the helpfull parasite

"the absolute of the host increases while its actual fitness decreases, and that of the parasite increases and the ecosystems looses bits"

black: host actual fitness; blue parasite actual fitness;  
red: host absolute fitness; yellow: collective fitnse (bits in population)
Conclusions

Ecosystem based solution feasible when mutation rate too high for individual to “fit in”

Difference between generation and maintainance of individual based solution

High mutation rates prevent large genomes. After prolonged evolution streamlining of genomes. Genome inflation facilitates evolvability.

*high mutation rate prevents genome expansion and compromises evolvability*
“Cooperation” (getting something done together) through spatial self-organization
Division of labor among predators
Coerces prey into certain types
See less – > can do more:
Cooperative solution of “all” problems, by “seeing” only a subset of problems
No direct or indirect fitness benefit for predators to give scavengers an eatable bite.

ecosystem based solution precedes individual based solution
ecosystem based solution stable at high mutation rates
ecosystem based solution preserves slightly beneficial genes