Solving Complex Problems with Coevolutionary Algorithms

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http://gecco-2017.sigevo.org/

GECCO '17 Companion, July 15-19, 2017, Berlin, Germany
ACM 978-1-4503-4939-0/17/07.
http://dx.doi.org/10.1145/3067695.3067705

Instructors

- **Krzysztof Krawiec** is an Associate Professor in the Laboratory of Intelligent Decision Support Systems at Poznan University of Technology, Poznań, Poland. His primary research areas are genetic programming and coevolutionary algorithms, with applications in program synthesis, modeling, image analysis, and games. Dr. Krawiec cochaired the European Conference on Genetic Programming in 2013 and 2014, the ACM GECCO GP track in 2015 and 2016, and is an associate editor of Genetic Programming and Evolvable Machines journal. His work in the area of CoEAs includes problem decomposition using cooperative coevolution, learning strategies for Othello, Go, and other games using competetive CoEAs, and discovery of underlying objectives in test-based problems.

- **Malcolm Heywood** is a Professor of Computer Science at Dalhousie University, Canada. His has a particular interest in scaling up the tasks that genetic programming (GP) can potentially be applied to. His current research is attempting the appraise the utility of coevolutionary methods under non-stationary environments as encountered in streaming data applications, and coevolving agents for single and multi-agent reinforcement learning tasks. In the latter case the goal is to coevolve behaviours for playing soccer under the RoboSoccer environment (a test bed for multi-agent reinforcement learning). Dr. Heywood is a member of the editorial board for Genetic Programming and Evolvable Machines (Springer). He was a track co-chair for the GECCO GP track in 2014 and a co-chair for European Conference on Genetic Programming in 2015 and 2016.

Agenda

- I. Introduction
- II. Competitive coevolution
  - Core concepts
  - One-population competitive coevolution
  - Two-population competitive coevolution
  - Advanced topics
- III. Cooperative coevolution
  - Core concepts
  - Case study: Evolving arbitrary sized teams
  - Case study: Diversity maintenance and policy reuse
  - Case study: Emergent policy reuse
  - Case study: Combining Competitive and Cooperative coevolution
- IV. Closing remarks

I. Introduction

Canonical assumptions made by EA

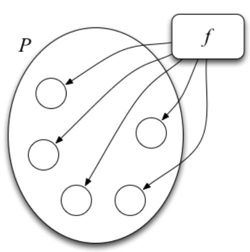
- An **absolute measure** of fitness is **available** and **computable**.
  - ‘Complete’ definition of task / environment
- Solutions are (more or less) **monolithic**.
  - Each individual encodes a **complete solution** to a problem
  - Tasks are not explicitly ***decomposed***.
- Coevolutionary algorithms (CoEA) **revise these assumptions**.

What is a coevolutionary algorithm?

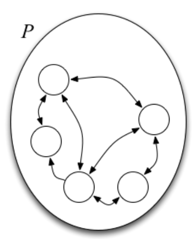
- A variant of EC where **fitness function mandates the individuals to engage into direct interactions.**
  - Fitness cannot be computed for isolated individuals.
- Formally:
  - Evolutionary algorithm (**EA**): $f: X \rightarrow E$
  - Coevolutionary algorithm (**CoEA**): $f: X_1 \times X_2 \times \ldots \times X_n \rightarrow E$, where E is an evaluation codomain (typically R)
  - **Interaction** = a tuple from $X_1 \times X_2 \times \ldots \times X_n$

EA vs. CoEA

EA
Absolute measure of fitness *f* available and computable for each individual separately.



CoEA
Search gradient can be obtained only by letting individuals interact. Exact fitness may be not computable.



Consequences

- Individuals' performances depend on each other (fitness is contextual)
- The solution of a problem can be:
  - An **element** of X_i (as in an EA)
    - Typical for ***competitive CoEA*** (with exceptions)
    - Key questions: What to evolve against? Who is the best teacher?
  - A **combination of elements** from X_is
    - Typical for ***cooperative CoEA*** (with exceptions)
    - Key questions: How to encourage cooperation? Divide and conquer.
- Pertains to so-called solution concepts, see later
- Remember: individual ≠ solution

What is it good for?

- CoEAs lend themselves conveniently to a few classes of problems of theoretical and practical interest.
- **Competitive CoEAs**: test-based problems, games, interactive domains
  - Example: individual=game strategy, fitness=expected game outcome
- **Cooperative CoEAs**: problem decomposition, modularity, credit assignment
  - Example: individual=a rule in a classifier, fitness=overall accuracy of the classifier
- Class of problems: co-search, co-optimization, generalized optimization (Wolpert and Macready 2005)

Other characteristics of CoEAs

- Operate under **incomplete information** (uncertainty)
- Focus on evaluation and **interaction schemes** (less so on search operators)
- Individuals often maintained in **several populations**.
- Biological analogs:
  - No global, static fitness function in Nature
  - Nature does not optimize for anything; EAs do.
  - Individual's fitness results from its interactions with environment, including other individuals of the same species

Measuring progress: Subjective vs. objective fitness

- **Subjective fitness**: f calculated using the currently available elements of X_is (a sample)
  - Typically those available in the current population,
  - Example: average game outcome against the opponents from the current population
- **Objective fitness**: f calculated with the elements chosen in a principled manner.
  Examples:
  - Average game outcome against all possible opponents
  - Game outcome against a human-crafted opponent.

II.1. Competitive coevolution

Class of problems tackled by competitive CoEAs

- Interactive domains
  - Sets of individuals (**entities***)
  - **Interaction function** (payoff function) $g: X_1 \times X_2 \times \ldots \times X_n \rightarrow R$
  - When n=2, the second argument is an opponent.
- Note: g alone does not define the search goal.
- What is the solution to the problem?

(*) Sometimes, but not always, identified with candidate solutions

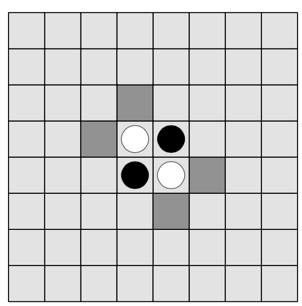
- Solution concept (cf. Ficici 2004, Popovici et al. 2012):
  - Criterion specifying whether a potential solution
    - is better than another solution (in **co-optimization**),
    - is solution to a problem (in **co-search**)
- Most popular SC: Maximization of Expected Utility (MEU): $f_o(x) = \mathrm{E}[\ g(x_1,x_2)\ ]$
  - A.k.a. generalization performance (Chong et al. 2008)
- Competitive CoEAs realize knowledge-free approach to solving problems posed in interactive domains.

Subjective fitness

- Challenge: calculation of f_o is often computationally infeasible.
  - Example: game of Othello: game tree complexity 10^{58}
  - Number of unique strategies typically much higher
- Solutions:
  - 1. **Fix the set of opponents.**
    - For instance, well-performing known opponents (e.g., handcrafted by humans)
    - Strong bias, limited generalization
  - 2. **Draw the opponents at random**
    - What is the 'right' distribution of opponents?
    - Drawing uniformly in the genotypic space does not result in desired (e.g., uniform) distribution of skills/capabilities
  - 3. **Competitive coevolution**

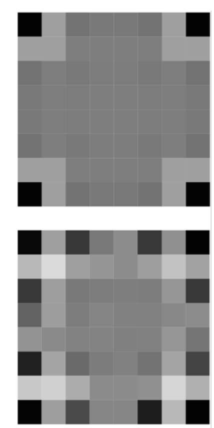
Example: Game of Othello

- Two-player, perfect-information, turn-based, zero-sum game
  - Still unsolved
  - Sudden changes of game state possible
- Strategy = candidate solution
- Competitive CoEA approach:
  - Evolve board evaluation function $b()$
  - Use it in one-ply search: simulate all legal single moves from the current state and choose the one that maximizes b.
- Popular representations of board evaluation functions: weighted piece counter and n-tuples



Weighted Piece Counter (WPC)

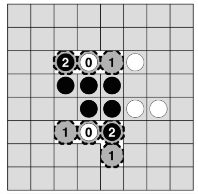
- Single linear neuron with 64 weights: $b(s) = \Sigma_i\ w_i s_i$
- Top: handcrafted Othello WPC board evaluation function (*standard WPC heuristics*)
- Bottom: a function evolved using one-population competitive CoEA, hybridized with temporal difference learning (TDL) (Szubert, Jaśkowski, Krawiec 2009)

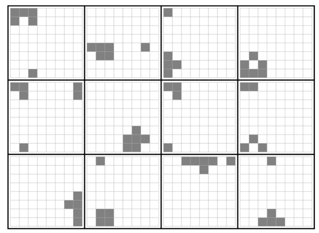


N-tuple networks

(Browning 1959, Lucas 1997)

- Combinatorial network with lookup tables holding all combinations for (usually randomly selected) subsets of (usually adjacent) board locations
- 3^n weights for a single *n*-tuple for tri-state boards (for Othello: empty, black, white)
- Top: 3-tuple and 4-tuple for base-3 numbers (white, empty, black):
  - $2{*}3^2 + 0{*}3^1 + 1{*}3^0 = 19$
  - $1{*}3^3 + 0{*}3^2 + 2{*}3^1 + 1{*}3^0 = 34$
- Bottom: Examples of CTDL co-evolved *n*-tuples (Szubert, Jaśkowski, Krawiec, 2013)





One-population competitive CoEA

- The simplest setup to approach MEU problems.
  - Applicable when $X_1 = X_2 = \ldots = X_n = X$
  - E.g. symmetric games
  - Usually: $f_s(x) = \Sigma_{x' \in X'}\, g(x,x')$, where X' is a sample drawn from current population P
- Interaction = single game (symmetric games) or two games (asymmetric games)
- Interaction schemes:
  - **Round-robin**: $n(n-1)/2$ interactions ($X' = P \setminus \{x\}$)
  - ***k*-random opponents**: kn interactions ($|X'| = k$)
  - **Single-elimination tournament** (SET): n interactions
    - Pair the individuals at random. Winners pass to the next stage. Fitness is the stage reached in the tournament.

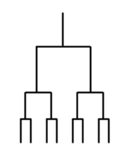
Highlights of one-pop competitive CoEAs

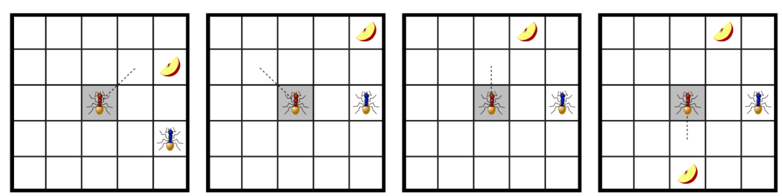
- Iterated Prisoner's Dilemma (Axelrod 1987)
- Backgammon (Pollack & Blair 1998)
- Checkers (Samuel 1959, Fogel 2002)
- NERO, Blackjack, Pong, Small-board Go, Tetris, …

Fitnessless Coevolution for Ant Wars

(Jaśkowski, Krawiec, Wieloch 2008)

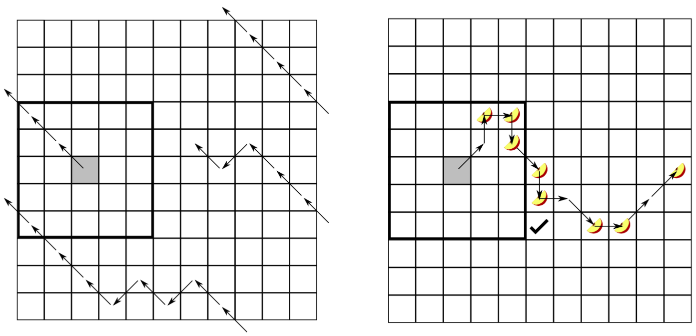
- FC: Pick *k* individuals at random. Run a SET on them and return the winner.
- Evolved the winner of the Ant Wars GECCO'08 contest
  - Two-player partially observable game
  - Agents (ants) see only a 5x5 fragment of the toroidal 11x11 board
  - The goal: collect more food pellets than the opponent.
  - Strategy representation: stateful GP program (intra-game memory)





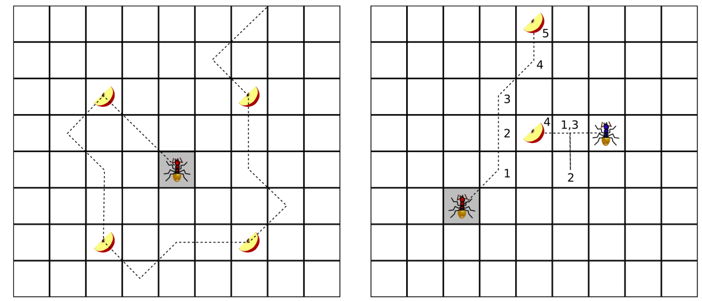
Example: Ant Wars

Complex behaviors emerged: **systematic search, rational choice of trajectories**, …



Example: Ant Wars

… **memorizing locations of food pellets, opponent avoidance, pseudo-suicide,** …



- Online demo: http://www.cs.put.poznan.pl/kkrawiec/antwars/

Digression: Importance of transitivity

- Fitnessless Coevolution is not equivalent to fitness-driven one-population coevolution if there are cycles in interactions in between individuals (Jaśkowski, Krawiec, Wieloch 2008)
- Example: Tic-tac-toe strategies A, B, C: place a mark in the numbered locations if free, otherwise in the location marked by asterisk (*)

A

1	2	3
		*

B

3		
2		
1		*

C

		1
	2	
3		*

- A beats B, and B beats C. But A does not beat C, just the opposite.
- Tic-tac-toe is **intransitive**.
- **No scalar fitness function** can model this (can realize only complete orders).

One-pop competitive CoEAs as self-learning

- Individuals create **search gradient** for each other.
  - A form of (population-level) **self-learning**
  - Can be seen as an analog to **self-play** in RL (individual-level)
- Q: Is this sufficient to guarantee progress?
- A: No.
  Coevolutionary pathologies are lurking out there.

Coevolutionary pathologies

- **Cycling**: evolution keeps rediscovering the same solutions
  - Particularly likely if game is intransitive.
- **Disengagement**: opponents are either trivial or way too difficult to beat.
- **Overspecialization** (**focusing**): mastering the skills of beating some opponents while neglecting the others.
- **Forgetting**: opponents defeated in the past turn out to be difficult again.
- See review and rigorous analysis in (Ficici 2004)
- Main causes:
  - No access to objective fitness
  - Population responsible for **both search and providing search gradient** for itself

Coevolutionary archive competitive CoEAs (one-population)

Archive = a container storing well-performing individuals, maintained alongside the population.

- Provides **long-term memory**
- Builds **search gradient**
- Prevents some **pathologies**
- Maintains **diversity** and **progress**

Archives help maintaining **historic progress** (Miconi 2009)

- Not necessarily progress in the global, objective sense.

How it works:

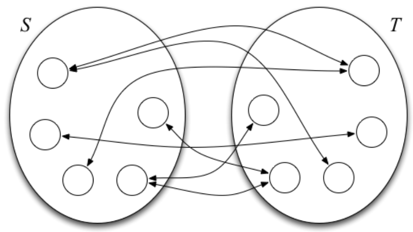
- Search algorithm submits some individuals to the archive
- Archive accepts some of them
- Individuals in population interact with peers **and** archival individuals
- Outcomes of interactions augment the fitness
- Simplest archive: best-so-far individual
- Hall of fame (Rosin & Belew, 1997)
  - Stores all best-of-generation individuals found so far
  - Population members play against each other and against the opponents from HoF

II.2. Two-population competitive CoEAs

Two-population competitive CoEAs

- One-pop competitive CoEA: Population responsible for both searching for good solutions and providing search gradient for itself.
  - Why not separate these functions?
- Two-pop competitive CoEAs: maintain separate populations of:
  - **candidate solutions** $S \subset X_1$ – intended to **solve the problem**
  - **tests** $T \subset X_2$ – **provide <u>only</u> search gradient** for the individuals in S
- Applicable in symmetric ($X_1 = X_2$) and asymmetric setting ($X_1 \neq X_2$)

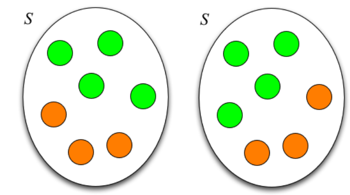
Two-population competitive CoEA



- Typical **interaction scheme**: all-to-all
- *S* and *T* co-evolve in parallel
- No transfer of individuals between *S* and *T*

How to evaluate the tests?

- Individuals in *S* rewarded for ***performing*** (aim at maximizing EU).
- **How to reward the tests** in *T*? Maximize EU as well?
  - Pathologies likely
  - Tests should be neither too easy nor to hard for the individuals in *S*
- Idea: reward tests for ***informing***, e.g.:
  - **Distinctions**: for every pair of distinguished solutions
  - **Informativeness**: for unique partitioning of *S*
  - Hybrids (e.g., with EU)



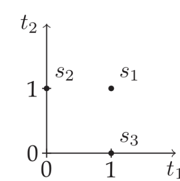
Test-based problems

- With two populations, the tests can be conceptually different from candidate solutions.
- **Test-based problem** (*S*, *T*, *G*, *Q*) (Popovici et al., 2012)
  - *G* – payoff matrix
  - *Q* – solution quality function
- Examples:
  - **Asymmetric games** (strategies vs. opponents)
    - E.g., tic-tac-toe, Othello,
  - **Control problems** (controllers vs. initial conditions)
    - Pole balancing, car control, etc.
  - **Learning from examples** (hypotheses vs. examples)
  - **Program synthesis** with GP (programs vs. tests)
  - In general: **co-optimization** and **co-search**
- Also applicable in symmetric settings

Pareto-coevolution

(Ficici and Pollack, 2001; Noble and Watson, 2001)

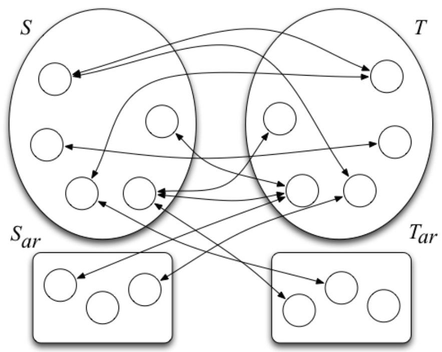
- Each test considered as a **separate objective.**
- Transforms a test-based problem into a **multiobjective optimization problem** (or many-objective one).
- Example:
  - s_1 solves both tests t_1 and t_2
  - s_2 solves only t_2
  - s_3 solves only t_1
  - s_1 **dominates** both s_2 and s_3



- Problem: **large number of tests** (and thus objectives).
- **Sparse** dominance relation.

Coevolutionary archives (two-pop)

- General scheme: individuals are **submitted** to archive and get **accepted or rejected** by it.
- **Separate archives** for solutions and tests



Coevolutionary archive algorithms (two-pop)

- **Iterated Pareto-Coevolutionary Archive**, IPCA (de Jong 2004)
  - A new solution s is added to S_{ar} if no $s' \in S_{ar}$ dominates s. In that case:
    - All $s'' \in S_{ar}$ dominated by s are removed from S_{ar}
    - The test t that made it possible for s to be added to S_{ar} is added to T_{ar}
  - Guarantees monotonous progress
  - Unlimited-size archive
  - Tests provide for **distinctions** between individuals
- **Layered Pareto-Coevolutionary Algorithm**, LAPCA (de Jong 2004)
  - Merges the current archive and the submitted elements and builds a Pareto ranking of solutions
  - The first k layers of the ranking remain in S_{ar}, the remaining ones are discarded
  - T_{ar} keeps the tests that support Pareto dominance in S_{ar}
  - No guarantee of monotonous progress, but (somehow) controllable size
- IPCA and LAPCA perform well only on small, usually artificial problems.

Coevolutionary archives

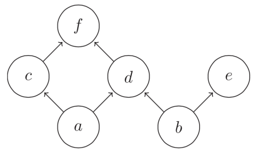
- Maintaining archives can be **costly**
  - Many interactions required to check if a solution should be added
- Mitigation: MaxSolve (De Jong 2005), for MEU solution concept
  - Keep in S_{ar} up to n solutions that solve the most tests (at least one), and in T_{ar} all tests that a solved by at least one $s \in S_{ar}$
  - [Behaviorally] duplicate tests are discarded
  - Monotonic: will not miss solutions that increase the number of solved tests
- When overhead of maintaining an archive counted in, non-archived algorithms can be equally efficient.
- Other types of archives (Jaśkowski & Krawiec 2010)
- Related concepts: **ideal evaluation** and **complete evaluation set** (E. de Jong and Pollack 2004)
  - The set of tests that preserves dominance relation between the solutions in S
  - Determining the minimal complete evaluation set is NP hard (Jaśkowski & Krawiec 2011)

II.3. Advanced topics in competitive coevolution

(selection)

Coordinate systems

- ❖ An interaction matrix defines a **dominance relation**
- ❖ Dominance relation defines a **partial order** in the set of individuals ⇒ partially ordered set, ***poset***

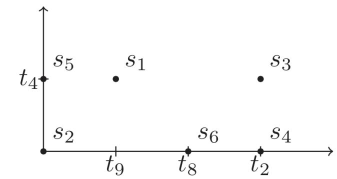


- ❖ A poset can be 'stretched' along multiple **dimensions** (**underlying dimensions**).
- ❖ Dimensions form a **coordinate system** (Bucci et al. 2004):
  - ❖ Axis = ordered list of tests (the most popular formulation)

Coordinate system: an example

- The game: Nim-1-3
  - Players in turns take sticks from two piles of size 1 and 3.
- Total of 144 strategies,
  - but only 6 behaviorally unique for the first player (*S*), and 9 for the second player (*T*).
- **Minimal** coordinate system
  - Some tests not needed to reproduce the dominance relation
- Game dimension: 2

	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9
s_1	1		1	1		1	1		1
s_2									
s_3	1	1	1	1	1	1	1	1	1
s_4	1	1	1				1	1	1
s_5	1			1			1		
s_6							1	1	1

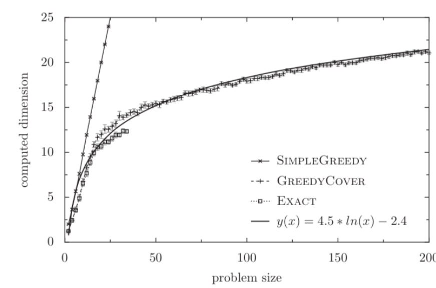


Coordinate systems: some results

- ❖ Can accelerate convergence and/or guarantee progress: Dimension Extraction Coevolutionary Algorithm, DECA (de Jong and Bucci 2006)
- ❖ Reveal the **internal structure of a problem** and relate to **problem difficulty**
- ❖ Hypothesis: dimensionality of coordinate system is a yardstick of **problem difficulty**
- ❖ The set of all tests forms the **complete evaluation set** (de Jong & Pollack 2004)
- ❖ Game dimension = **width of the poset** (Jaśkowski & Krawiec 2011)
- ❖ The number of underlying objectives for an abstract problem seems to be limited by a logarithm of the number of tests.

Problems with exact coordinate systems

- ❖ Problem dimension may be **underestimated** when only samples of *S* and *T* are used.
- ❖ Finding minimal CS for a problem is **NP-hard** (Jaśkowski & Krawiec 2011)
- ❖ Heuristics exist but **overestimate** the number of dimensions
- ❖ Nontrivial test-based problems have **very high dimensionality**
- ❖ Q: Can we efficiently **'approximate' the underlying dimensions**?



Heuristic discovery of underlying objectives

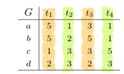
- Idea:
  - Construct **efficiently** approximate underlying objectives from the information available at the given stage of search process
  - Use the derived objectives in multiobjective EA setting
- **Derived objectives** rather than **underlying objectives**
  - **Approximate** (do not reproduce the original dominance)
  - **Transient** (depend on the current populations)
- Technical means: **clustering** of tests

Heuristic discovery of underlying objectives

(Krawiec & Liskowski 2015, Liskowski & Krawiec 2016)

$S = \{a, b, c, d\}$ $T = \{t_1, t_2, t_3, t_4\}$

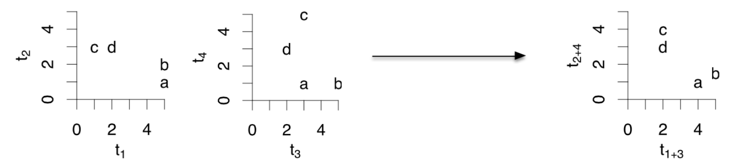
G	t_1	t_2	t_3	t_4
a	5	1	3	1
b	5	2	5	1
c	1	3	3	5
d	2	3	2	3



objective compression

derived objectives t_{1+3} and t_{2+4}

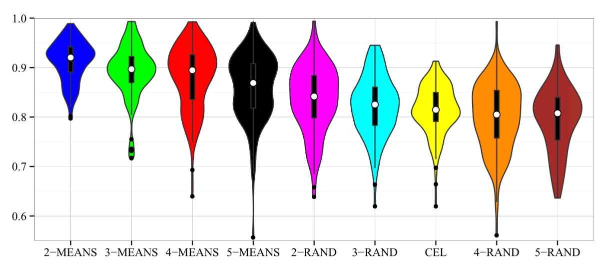
G'	t_{1+3}	t_{2+4}
a	4	1
b	5	1.5
c	2	4
d	2	3



Upside: denser dominance relation. Downside: 'false positive' dominance possible

Heuristic discovery of underlying objectives

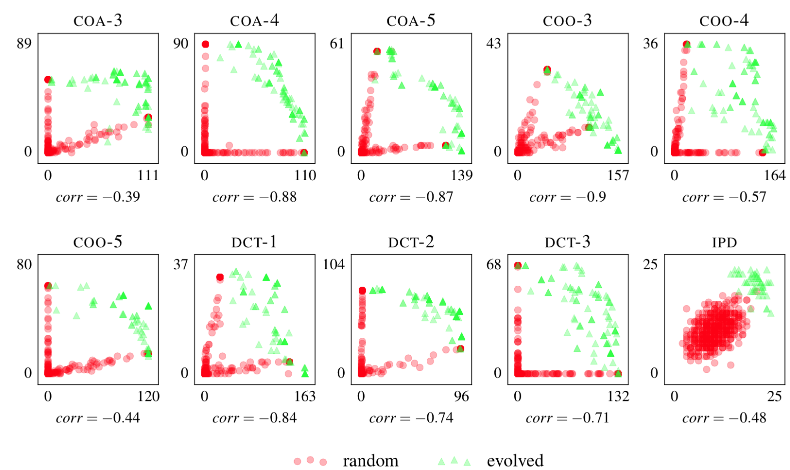
- Results for 9-choice iterated prisoner's dilemma, IPD (MEU)
  - *k*-MEANS: *k* objectives derived using *k*-means clustering algorithm
  - *k*-RAND: objectives built by random partitioning of tests into *k* objectives



- Applied also in non-coevolutionary setting with GP, with *k* adjusted automatically (Krawiec & Liskowski 2015). Better than GP and RAND, comparable to IFS.

Heuristic discovery of underlying objectives

(Liskowski & Krawiec 2016)



Genetic Programming: Program synthesis as a test-based problem

- In GP, programs are evaluated by confronting them with (a sample of) tests
  - S = population of candidate programs
  - T = population of tests (fitness cases)
- Simple variant: Pairwise Comparison of Hypotheses (Krawiec 2001)
- Fully-fledged coevolutionary approach: (Arcuri & Yao 2014)
  - Synthesis from formal specification (precondition + postcondition)
  - Co-evolving sets of unit tests in T alongside with programs in S
  - Strongly-typed GP
  - Tested on nontrivial benchmarks: MaxValue, AllEqual, TriangleClassification, Swap, Order, Sorting and Media
  - Better than random sampling of tests (particularly when using specialized sub-populations corresponding to parts of formal specification)
- Related: collecting test cases from program verification in spec-based GP (Krawiec, Bladek, Swan 2017)

Hybridization with RL

- CoEAs are **generate-and-test** techniques (like EA)
  - In contrast, **gradient-based** methods provide 'directed' corrections/updates of parameters
  - Can be more efficient in high-dimensional problems
  - Complementary: CoEAs learn slower than TDL but eventually outperform it (Lucas & Runarsson 2006)
- **Coevolutionary Temporal Difference Learning**, CTDL (Krawiec & Szubert 2011, Szubert et al. 2013)
  - Interleave one-population coevolution (with round-robin) with TD(0)
  - CoEA picks the 'right' opponents, TDL tunes the solutions in a self-play mode
  - CoEA modifies the topology of n-tuples. TDL only affects the weights.
- A form of **memetic algorithm** (genetic local search) (Moscato 1989): individuals' interactions with the environment influence their genotypes (Lamarckian evolution).
- Related to: **adversary reinforcement learning**

Hybridization with RL

- Othello, *n*-tuples (Szubert, Jaśkowski, Krawiec 2013)
  - Compared also to ETDL= EA+TD(0)
- Othello Evaluation Function League
  - Ranked according to average performance against *standard heuristic* WPC (handcrafted strategy; moves partially randomized) (as of 2011)
  - http://algoval.essex.ac.uk:8080/othello/html/Othello.html
- ETDL better on predefined opponent (heuristic WPC)
- CTDL produces more versatile players

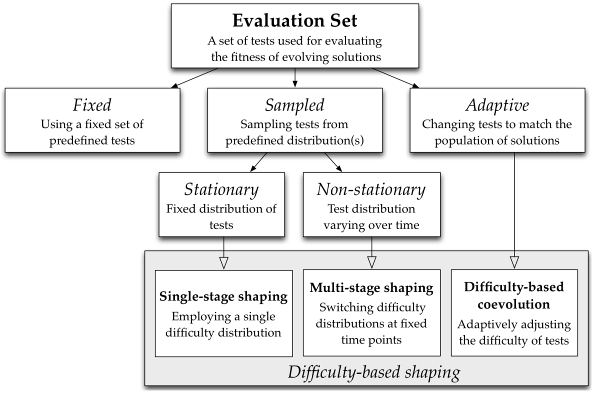
OTHELLO LEAGUE RANKING

Name	Size	Played	Won	Drawn	Lost
epTDLmpx_12x6	12 × 6	100	89	1	10
prb_nt30_001	30 × 6	100	84	0	16
prb_nt15_001	15 × 6	100	83	3	14
epTDLxover	12 × 6	100	81	4	15
t15x6x8	15 × 6	100	79	3	18
SelfPlay15	12 × 6	100	77	0	23
tz278_2	278 × 2	100	76	3	21
Nash70	12 × 6	100	72	4	24
x30x6x8	30 × 6	100	71	4	25
pruned-pairs-56t	56 × 2	100	71	1	28

Coevolutionary shaping

- Shaping = key concept in behavioral psychology (Skinner 1938)
  - **Expose the learner to a series of training episodes of gradually increasing difficulty.**
  - Motivation: Tasks can be too difficult to learn autonomously.
  - Example: To train a pigeon to strike a ball, first reward looking at it, then approaching it, and only then striking the ball with the beak.
- Used with success in Reinforcement Learning, e.g. pole balancing (Selfridge 1986)
  - Simplified version of tasks generated by relaxing/parameterizing the original one
  - E.g. change the length of the pole, increase the mass, etc.
- Related to: **incremental evolution, staged evolution, environmental complexification**
- Requires human intervention (decide how to relax the tasks, order them, etc.)

Coevolutionary shaping



Bottom line: Coevolutionary shaping works as well as manual shaping, but requires **less parameter tuning** (Szubert 2014, Szubert et al. 2013)

Competitive Coevolution: Key take-home messages

- A competitive CoEA **can** guide itself towards the optimum, even though it does not have access to objective fitness.
  - However, this can be ineffective due to **pathologies**.
- Archives (and populations of tests in two-pop coevolution) form long-term memory and **accumulate knowledge** about a problem.
- Coordinate systems and **underlying objectives** are examples of alternative **search drivers**.
  - Aim at widening the 'evaluation bottleneck' and making search algorithm **better-informed.**
- CoEAs are particularly effective for **adversarial problems**.
  - Many problems of practical interests can be posed in this way.

Not covered in this tutorial

- Measuring and visualizing progress (e.g., CIAO plots)
- Artificial problems: number games. Strategies represented as vectors of n elements.
  - **Compare-on-all:** A solution wins if it is better on all elements
  - **Compare-on-one:** a test picks a dimension at random; the solution wins if it's greater on that dimension
- Other solution concepts (Ficici 2004, Poppovici et al. 2011)
  - Simultaneous maximization of all outcomes, Nash equilibrium, Pareto-optimal set, Algorithms: (Ficici 2004) and review in (de Jong 2005)
- Deciding upon the final outcome of a CoEA: "output mechanism" (Popovici and Winston 2015)
- Random Sampling Evolutionary Algorithm (Chong et al. 2008) - no true coevolution, but hard to beat using competitive CoEAs.
- Coevolutionary free lunches (Wolpert & Macready 2005; Service and Tauritz 2008; Popovici and Winston 2015)
- Hybridization with CMA-ES (Jaśkowski & Szubert, 2015)
- In-depth analysis of relations between test-based co-optimization and supervised learning (Popovici 2017, to appear)

III. Cooperative Coevolution

Cooperative Coevolution

- **Answers the question:**
  - How to encourage collaboration?
- **Metaphor:**
  - Divide and conquer!
- **Why (is it useful?): Promoting modularity / reuse**
  - additional clarity in: (relative to a monolithic solution)
    - credit assignment
      - search space projected into multiple smaller search spaces
      - agents do not need to solve all the task
    - solution transparency
    - capacity to react to changes (Simon's parable of the two watch makers)
- **Fitness: who to credit for what?**
  - generalist pathology:
    - individuals rewarded for maximizing the number of collaborations
    - stable / mediocre solutions rather than optimal solutions

A Metaphor…

- "species [individuals] represent solution components. Each individual forms a part of a complete solution but need not represent anything meaningful on its own. The components are evolved by measuring their contribution to complete solutions and recombining those that are most beneficial to solving the task." [Gomez et al., (2008)]
- **Central questions**
  - How to:
    - How to compose a candidate solution (team)
    - distinguish between credit to the team versus that to team members
    - Learn **context**
    - **Maintain diversity**

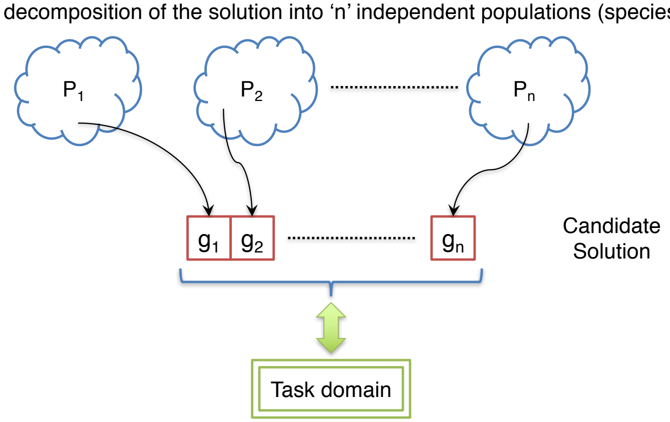
Cooperative Coevolution for complex systems : Some milestones

- **Neural Networks**
  - Moriarty, Miikkulainen (1998)
  - Potter & de Jong (2000)
  - Gomez et al. (2008)
  - Gomes et al. (2016)
- **Genetic Programming**
  - Krzystof & Bhanu (2006, 2007)
  - Thomason & Soule (2007), Rubini et al. (2009)
  - Lichodzijewski & Heywood (2008)
  - Wu & Banzhaf (2011)
- **Formulating fitness functions**
  - Panait et al. (2006, 2008)
  - Agogino & Tumar (2008), Knudson & Tumar (2010)
- **Diversity maintenance**
  - Lichodzijewski et al. (2011)
  - Doucette et al. (2012)
  - Kelly & Heywood (2014)
- **Non-stationary tasks**
  - Agogino & Tumar (2008)
  - Vahdat et al, (2015)
- **Reinforcement Learning**
  - Moriarty & Miikkulainen (1998)
  - Gomez et al. (2008)
  - Agogino & Tumar (2008), Knudson & Tumar (2010)
  - Rubini et al. (2009)
  - Doucette et al. (2012)
  - Kelly & Heywood (2017a,b)

Cooperative Coevolution: An architecture

(Potter & De Jong, 2000)

Prior decomposition of the solution into 'n' independent populations (species)



Biased and Lenient cooperation

(Panait et al., 2006), (Panait et al., 2008)

Biased cooperation

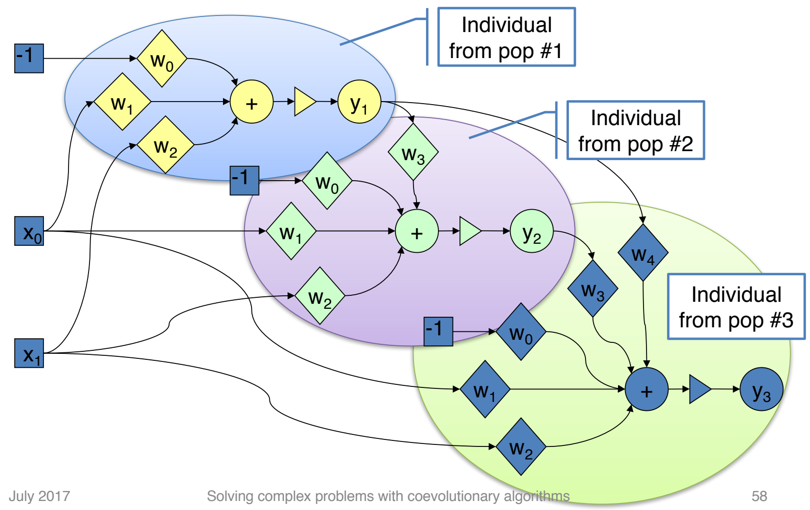
- Consider team versus individual fitness
  - Individuals receive avg. of fitness from teams
  - Promotes generalists
  - Hitchhiking
- Recommend defining individual fitness as
  - an *optimal* team of collaborators
  - Not clear how an *optimal* collaborator set is found in the general case

Lenient cooperation

- Individual fitness
  - $\text{MAX}_{i \text{ in team}}$ (team$_i$ fitness)
  - Hitchhicking still exists
  - Is hitchhiking all negative?
    - Enables individuals to find their niche
    - Provides a memory of previous / alternative policies

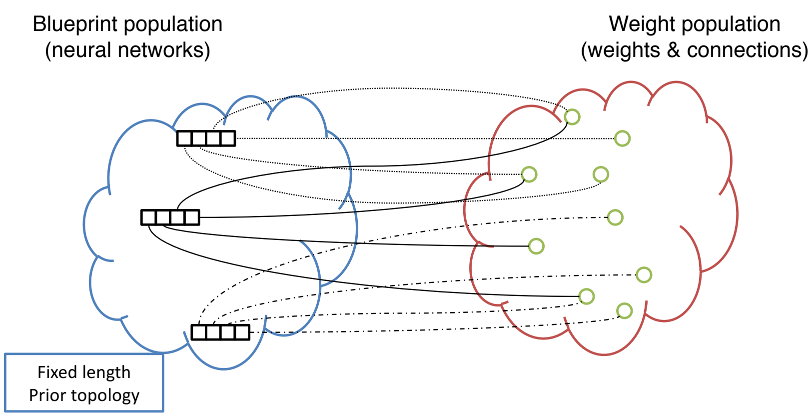
Coevolving a cascade network

(Potter & De Jong, 2000)



SANE with blueprints

(Moriarty & Miikkulainen, 1998)



Difference evaluation functions

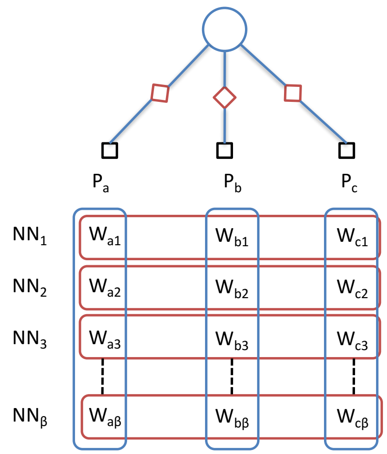
(Agogino & Tumar, 2008), (Knudson & Tumar, 2010), (Codly & Tumar, 2012)

- **Global fitness**
  - Performance of entire collective
  - Difficult to identify the contribution from each agent
- **Local fitness**
  - Performance of single agent
  - Difficult to encourage non-overlapping collective behaviours
- **Difference evaluation function (D_i)**
  - Explicitly estimate value added by agent 'i'
  - Global fitness needs to be locally 'decomposable'
  - Agents assigned w.r.t. physical locality to distributed sub-tasks
  - Form of 'spatial embedding'
- **D_i formulation**
  - $D_i = G(s) - G(s_{-i} + C_i)$
- G(s)
  - G(•) is the global evaluation function
  - 's' state of the system
- s_{-i}
  - States for which agent 'i' have no contribution
- C_i
  - Default vector of constants
- Observations
  - In the worst case s_{-i} is empty
    - Agent 'i' impacts on all states
  - D_i directly expresses the impact of agent 'i' not present
  - Limited by capacity to design appropriate `difference' expression

Cooperative Synapse NeuroEvolution

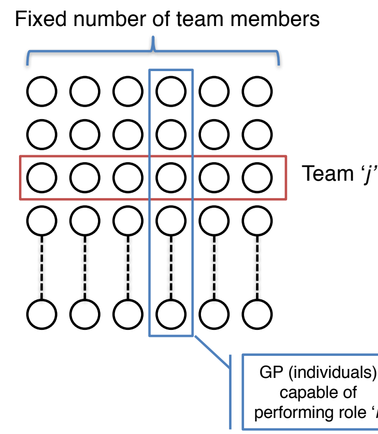
(Gomez et al., 2008)

- ❖ Select Parents
  - ❖ NNs (say, top 25%)
- ❖ Variation
  - ❖ 75% children
- ❖ Sort $\mathbf{P}_i$ w.r.t. $f(\boldsymbol{w}_{ij})$
  - ❖ $\mathbf{P}_i$: $f(\boldsymbol{w}_{i1}) > f(\boldsymbol{w}_{i2}) > \ldots f(\boldsymbol{w}_{i\beta})$
- ❖ Stochastic permutation of $\mathbf{P}_i$ content
  - ❖ $\mathbf{P}_i$: $f(\boldsymbol{w}_{i1})$ $f(\boldsymbol{w}_{i2})$ … $f(\boldsymbol{w}_{i\beta})$



Orthogonal evolution of (GP) teams (1)

(Thomason & Soule, 2007), (Rubini et al., 2009)



- ❖ **Motivation**
  - ❖ Team selection:
    - ❖ Good cooperation
    - ❖ Poor individual fitness
  - ❖ Island (individual) selection:
    - ❖ Poor cooperation
    - ❖ Strong individual fitness
- ❖ **OET1 (OET2)**
  - ❖ Select w.r.t individuals (teams)
  - ❖ Replace w.r.t. teams (individuals)

Orthogonal evolution of (GP) teams (2)

(Thomason & Soule, 2007), (Rubini et al., 2009)

OET1

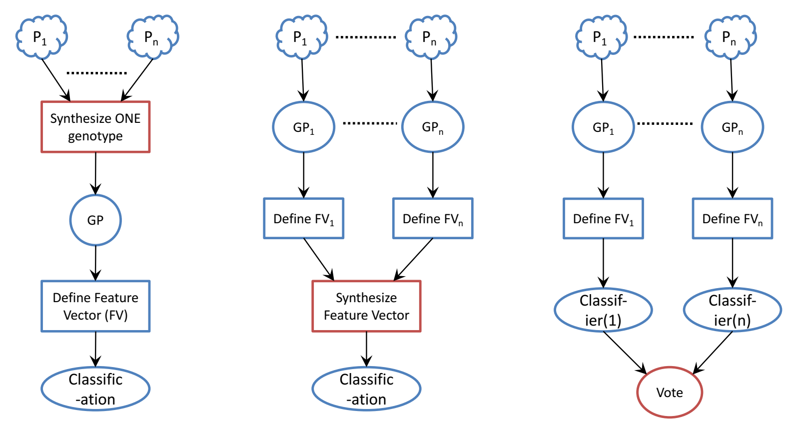
- ❖ Team = NULL
- ❖ *Select* **best** individual per role
- ❖ Create 2 such teams
- ❖ Apply variation operators
- ❖ Evaluate fitness
- ❖ *Replace* **worst teams**

OET2

- ❖ *Select* **2 best teams**
- ❖ Apply variation operators
- ❖ Evaluate fitness
- ❖ Award fitness to individuals in same team
- ❖ *Replace* **weakest** individuals

Level of Decomposition

(Krawiec & Bhanu, 2005), (Krawiec & Bhanu, 2007)

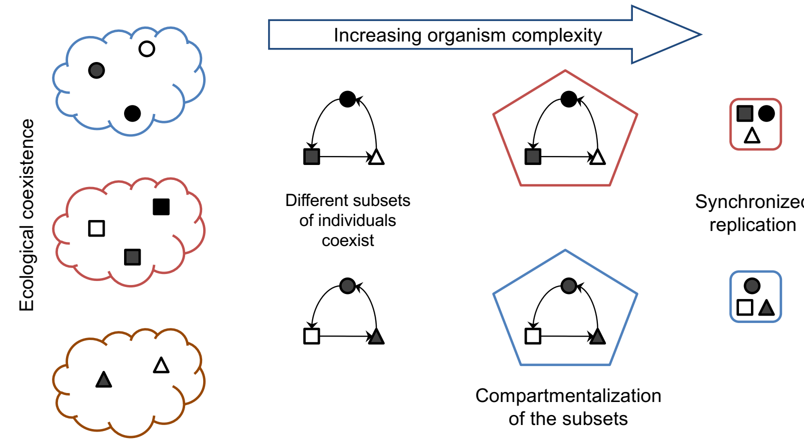


III.1 Case Study – Evolving arbitrary sized teams

Symbiosis, diversity maintenance, and separating action from context

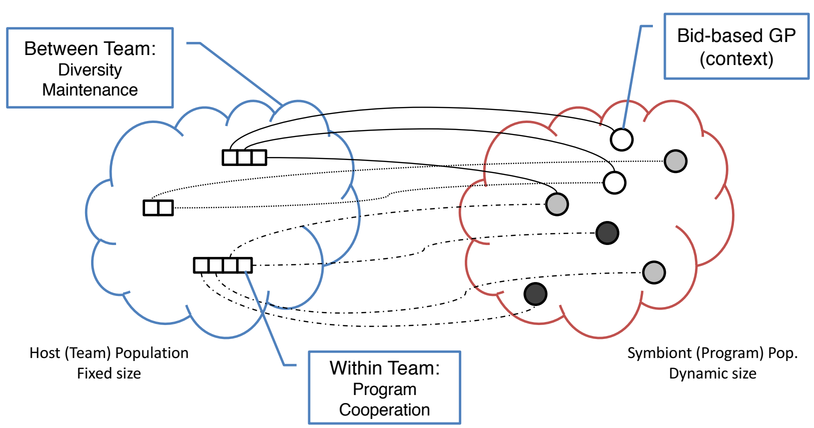
Abstract Model of Symbiosis

(Maynard Smith, 1991)



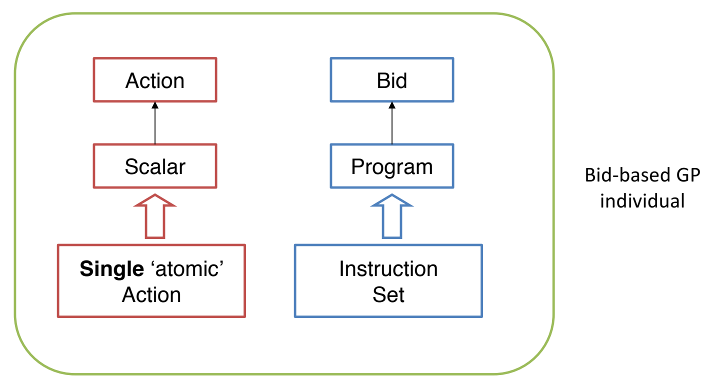
Symbiotic Bid-Based GP (SBB)

(Lichodziejewski & Heywood, 2008, 2010)



Achieving Symbiont Context

Bid-based GP



Team (Host) Fitness

- **Outcome vector, G(•)**
  - Point (p(k)) to Team/Host (h(i)) Outcome

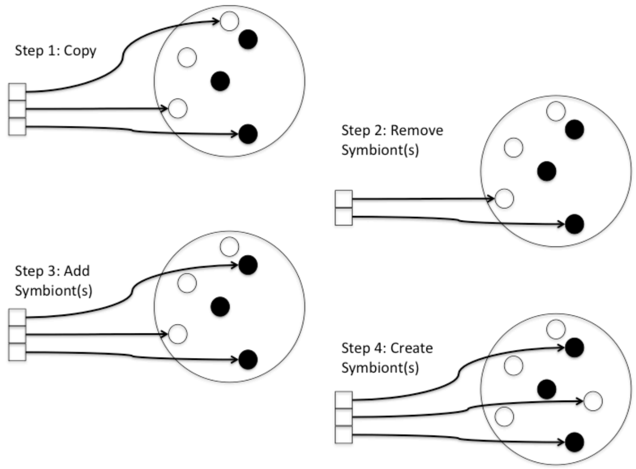
G(h(i), p(k)) = Domain specific reward on training case p(k)

- **Inter Host Diversity Maintenance**
  - Fitness sharing (see also behavioural and novelty measures)

$$s_i = \sum_k \left(\frac{G(h_i, p_k)}{\sum_j G(h_j, p_k)} \right)$$

Asexual Reproduction

Species independence



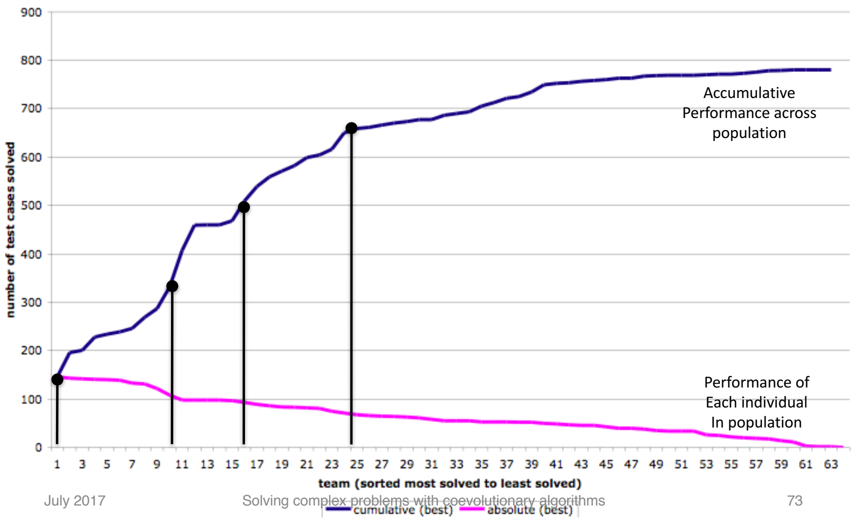
Supervised learning

- Multi-class classification
  - (Lichodzijewski & Heywood, 2008)
- Monolithic GP versus Teaming GP
  - (Lichodzijewski & Heywood, 2010)
- Decomposing large attribute spaces
  - (Doucette et al., 2012a)
- Streaming Classification
  - (Vahdat et al., 2015), (Khanchi et al., 2016)

III.2 Case Study – Diversity maintenance and Policy reuse

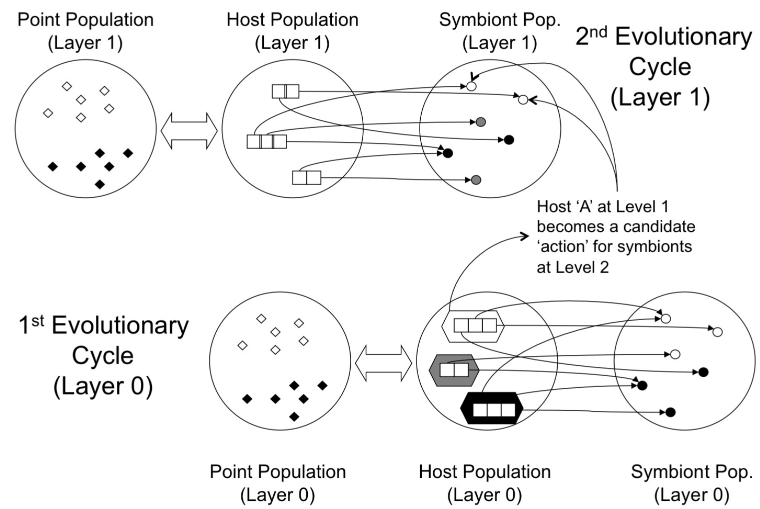
Hierarchical organization of programs, program abstraction

Motivation – Population fails in task



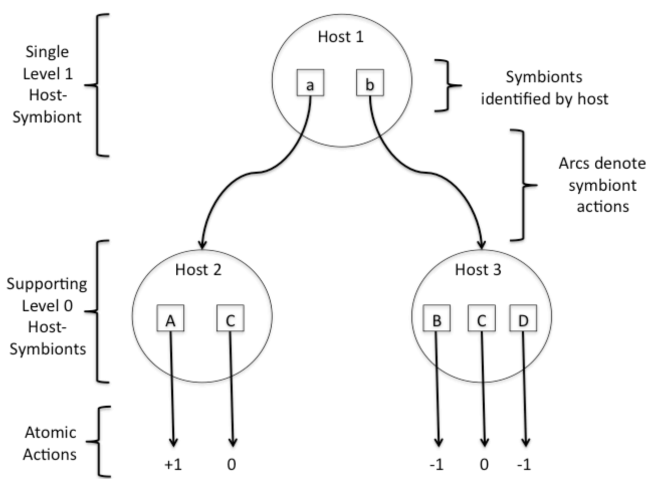
Evolving a policy tree

(Doucette et al., 2012b), (Kelly & Heywood 2014, 2015), (Smith et al, 2016)



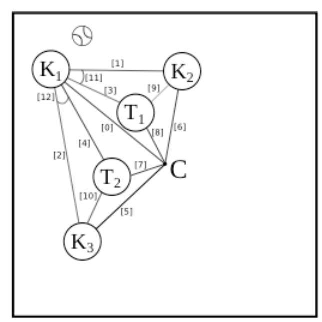
Evaluating a policy tree

(Doucette et al., 2012b), (Kelly & Heywood 2014, 2015), (Smith et al, 2016)

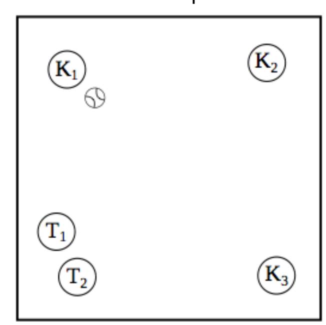


Keepaway soccer

Task definition (Stone et al, 2005)



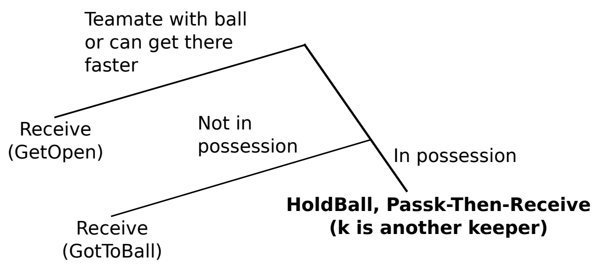
Game initial state
-- Stochastically defined
-- Robocup server



State variables
-- takers to keepers
-- ball assumes similar description

Interface to policy learner

Prior 'keeper' decision tree
Stone et al, (2005)



'Novelty' style diversity metric

(Kelly & Heywood, 2014)

- All start states the 'same'
- Encourage diversity in failure (novelty)

Reward of individual 'h_i' on game 'e_j'

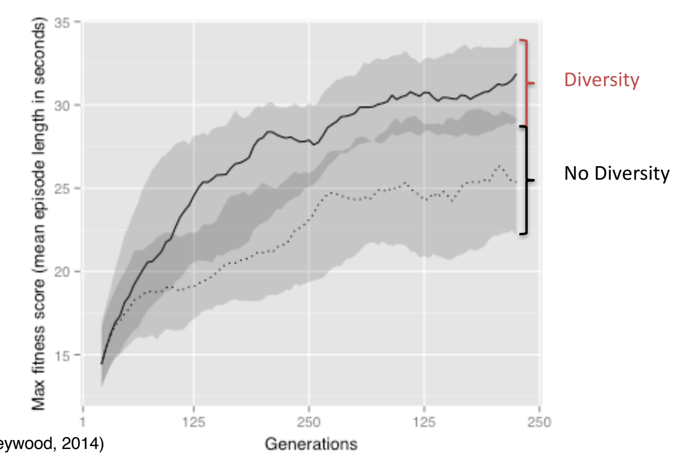
$$s_i = \sum_{j \in h_{hist}} \left(\frac{G(h_i, e_j)}{\sum_{k \neq i}(1 - dist(e_j, e_{hist}))G(h_k, e_{hist})} \right)$$

Distance between current game (e_j) and 'closest' historical game (ehist) for alternate solution (hk)

Reward of alternate individ. (h_k) in historical game (e_{hist})

Keepaway TRAINING performance

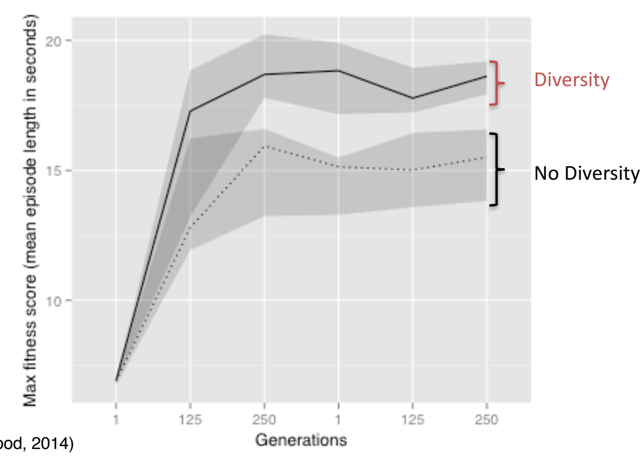
With / Without diversity



(Kelly & Heywood, 2014)

Keepaway TEST performance

1000 games, Sampled at intervals of 125 generations



(Kelly & Heywood, 2014)

III.3 Case Study – Multi-task learning under Atari console

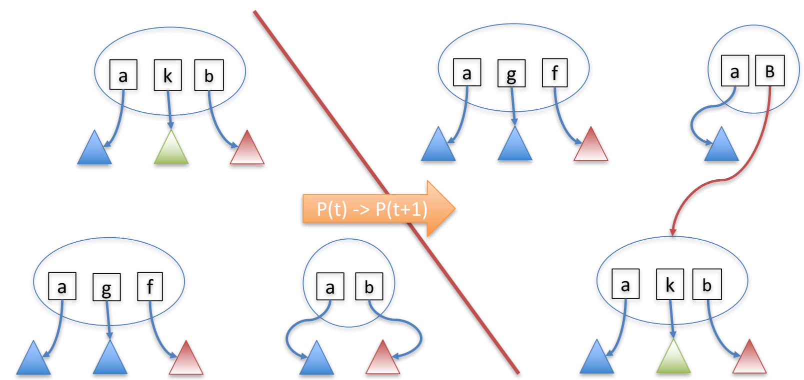
Program ‘connectivity’ organized through an emergent process

Tangled Program Graph representation

Single policies play multiple games

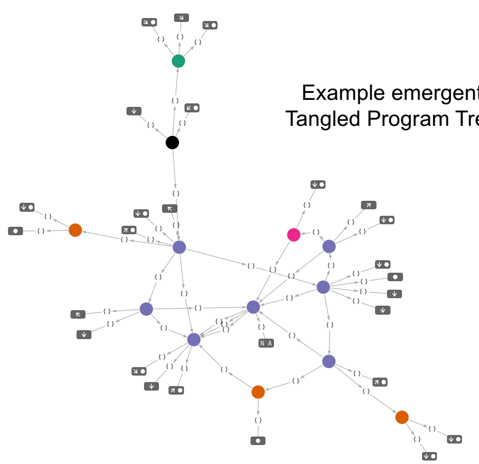
Tangled Program Graphs

(Kelly and Heywood, 2017a, 2017b)

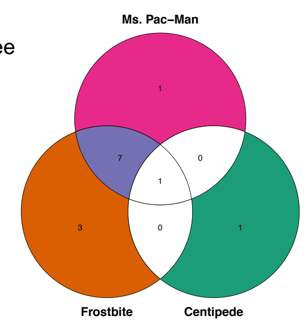


Playing *Multiple* Atari game titles

(Kelly & Heywood, 2017b)



Example emergent Tangled Program Tree



III.4 Case Study – Combining Competitive and Cooperative coevolution

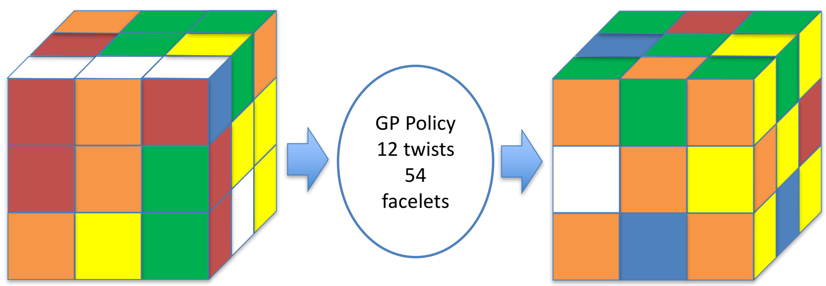
Evolving `Deep’ policy hierarchies

Select Rubik’s Cube configurations Competitively

Coevolve teams of programs through independent cycles of evolution

Learning optimal policies for Rubik's Cube state

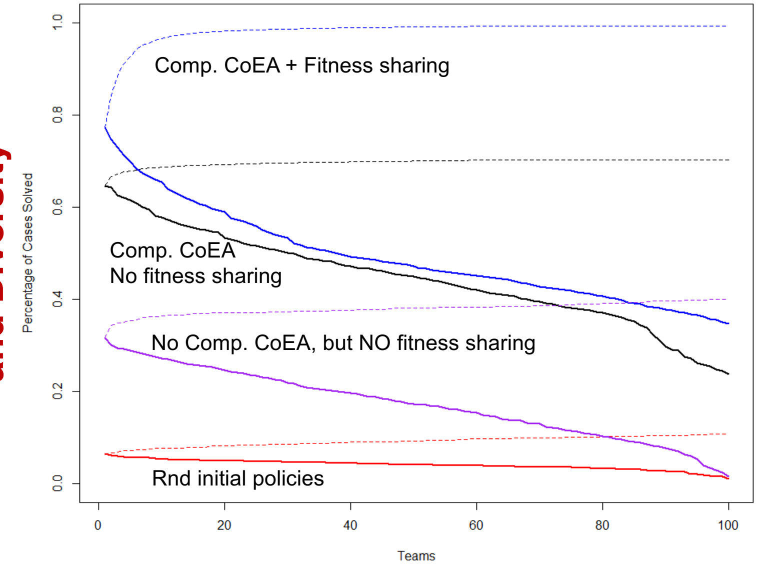
(Smith & Heywood, 2017)



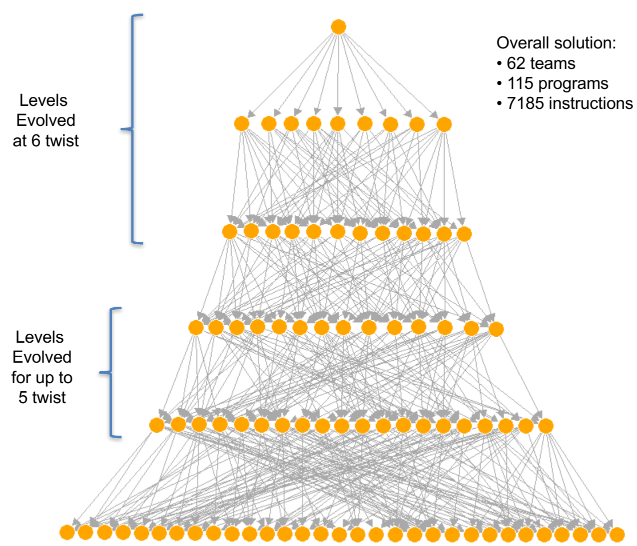
Scrambled Cube

Goal: 4th Sub-group

Contribution of Competition and Diversity



Solution Complexity at 6-twist



Cooperative Coevolution

Concluding Comments (1 of 2)

- Highlights
  - Separation of context and action
    - Arbitrary team sizes under GP
  - Maintaining Diversity significant
    - Making diversity metrics 'task free'?
  - Reuse of previous policies leverages diversity for generalization
    - Strict cycles of reuse: **hierarchical policy trees**
    - Continuous discovery of modularity: **emergent tangled program graphs**
  - Solutions generally simpler than monolithic models
    - Real-time execution under modest computational support
  - React to changing environments more effectively

Cooperative Coevolution
Concluding Comments (1 of 2)

- **Some open questions (a non exhaustive list!)**
  - Credit for collective versus individuals
  - What learning bias are most appropriate for diversity maintenance
    - Task specific metrics
      - E.g., (Nelson et al. 2009)
    - … versus task independent metrics
      - Novelty as an objective (Gomes, Christensen 2013), (Gomes et al., 2016)
      - Compression distance (Gomez, 2009)
      - Connectivity biases (Clune et al., 2013)
      - Intra Team diversity (Kelly, Heywood, 2015), (Gomes et al., 2016)
    - … versus how to 'present' diversity
      - Pareto Multi-objective versus **switching** between multiple diversity metrics (Donieux, Mouret, 2013)
  - Cooperative coevolution and code reuse
    - Supervised learning (Lichodzijewski and Heywood, 2008, 2010), (Jaskowski et al., 2014)
    - Reinforcement learning (Kelly and Heywood, 2014, 2015, 2017a,b), (Didi and Nitschke, 2016), (Smith and Heywood, 2017)
  - Specialization versus generalization
    - Heterogeneous versus Homogeneous deployment of policies within teams (Waibel et al., 2009), (Nitschke et al., 2012)

Cooperative Coevolution
Example Benchmark task domains

- **Feature identification to classification**
  - K. Krawiec, B. Bhanu (2006, 2007); W. Jaskowski et al., (2014)
    - Constructing hierarchal models for feature extraction and classification
- **Double inverted pendulum / cart pole**
  - Gomez et al, (2008)
    - Capacity for solving the task
- **Acrobot**
  - Doucette et al, (2012b)
    - Capacity for solving the task / generalization
- **Predator-prey strategies**
  - Nitschke et al., (2012); Yong and Miikkulainen (2009); Rawael et al., (2010); Gomes et al., (2016)
    - Task decomposition and collective problem solving
- **Distributed multi-object location**
  - Agogino, Tumar (2008); Knudson, Tumar (2010); Colby, Tumar (2012)
    - Task decomposition and (heterogeneous) collective problem solving
- **Keepaway or Half field offense (soccer)**
  - Kelly, Heywood (2014, 2015), (Didi and Nitschke, 2016)
    - Task decomposition and (homogeneous) collective problem solving
    - Capacity for task / generalization through hierarchical code reuse
- **Strategies for solving the Rubik's Cube**
  - (Smith et al., 2016), (Smith and Heywood 2017)
    - Task decomposition and capacity for task / generalization through hierarchical code reuse
- **General video game playing agents**
  - (Kelly and Heywood, 2017a,b))
    - Emergent Tangled Program Graphs from video screen capture for game playing agent policies

IV. Closing remarks

Closing remarks

- Coevolutionary algorithms = conceptually interesting and oftentimes efficient paradigm for solving complex problems
- Addresses key aspects of computational intelligence:
  - What/who to learn from?
  - How to drive the search/optimization?
  - What is solution to my problem?
  - How do I decompose my problem?
  - How do I make some entities cooperate?
- Many interesting results,
  - … even more open questions!

Acknowledgements

- The content of this tutorial has benefited from a host of collaborations over the years including, but not limited to:
  - John Doucette, Wojciech Jaśkowski, Stephen Kelly, Peter Lichodzijewski, Paweł Liskowski, Robert Smith, Marcin Szubert, Ali Vahdat, Bartosz Wieloch
- MIH would like to acknowledge funding for aspects of research reported on in this tutorial from the NSERC Discovery and CRD programs (Canada).
- KK would like to acknowledge funding for aspects of research reported on in this tutorial from the National Science Centre and National Centre for Research and Development (Poland, grant 2014/15/B/ST6/05205).

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