From Software Architecture to Software Gardening: New Paradigms for the Development of Complex Adaptive Systems

Thomas Gabor, LMU Munich
RoSI Lecture 2019-12-16
The Big Picture

**Complex Adaptive Systems**

- Complexity
- Dynamicity
- Trust
The Big Picture

Software Architecture

Complex Adaptive Systems
- Complexity
- Dynamicity
- Trust
The Big Picture

Software Architecture

Complex Adaptive Systems
Complexity
Dynamicity
Trust

preserve initial consistency throughout development
The Big Picture

Software Architecture

preserve initial consistency throughout development

Complex Adaptive Systems

Complexity
Dynamicity
Trust

continuously (re-)establish (partial) consistency from initial inconsistency
The Big Picture

Software Architecture

preserve initial consistency throughout development

Software Gardening?

continuously (re-)establish (partial) consistency from initial inconsistency
The Small Picture

▷ robot starts top left
▷ must visitworkstations
  of specific colors
  in specific order
▷ must not collide
  with obstacles
▷ should choose
  the shortest path
The Small Picture

system

test
System and Test

system ➔ test
Adaptive Systems

Diagram showing behavior over situations comparing classical system and adaptive system.
Adaptive Systems

Adaptation could be realized by...
- Reinforcement Learning
- Optimization Algorithms
- many more

behavior

situations

adaptive system
classical system
Optimizing Adaptive Systems

Optimal behavior may change dynamically with respect to goal function.

Adaptive system
Classical system
Orange is at least as adaptive as Red

<=>

Orange can solve at least the situations Red can solve

AND Orange performs at least as close to the optimum as Red
System and Test

adaptation

system

→

test
System and Test

adaptation

better system

test
System and Test

adaptation

even better system

test
If an adaptive system is much more powerful than its test, then it may prefer tricking the test to solving its actual objective.
Tests

situations

behavior

test case
Tests of Adaptive Systems
Tests of Adaptive Systems
Tests of Adaptive Systems

scenarios
- logical constraints
- test cases

requirements
- use cases
- data points

realized baseline components

behavior
- test generator
- situations
- test case

realized baseline components
Green is at least as hard as Purple

\[ \text{Green} \leq \text{Purple} \]

For every scenario generated by Purple, Green generates a scenario that is at least as close to optimal behavior.
System and Test

adaptation

even better system

adaptation

test
System and Test

adaptation

even better system

adaptation

better test
System and Test

adaptation

even better system

adaptation

even better test
System and Test

adaptation

even better system

is tested by

adaptation

even better test
System and Test

adaptation

even better system

is tested by

is used for training

even better test
System and Test

adaptation

even better system

is tested by

is used for training

adaptation

even better test

arms race between system and test

Scenario Co-Evolution
Coevolution
Coevolution
Coevolution
Coevolution
Coevolution

When you have too many mice, keep a cat.

When you need your lawn mown, keep sheep.
Scenario Co-Evolution with Reinforcement Learning and Evolutionary Algorithms
The Small Picture

system

test
The Small Picture

system

Reinforcement Learning

Random Generator

test
Reinforcement Learning

Random Initialization → Decision → Execution → Reward → Result

Training
Training against Random Test

System

Test

Reinforcement Learning

Random Generator
Training against Random Test
Training against Random Test

Random Generator → Test → System
Training against Random Test

Random Generator

Test

Scenarios

System
Training against Random Test

Random Generator → Test Scenarios

reinforce

System
Training against Random Test

Random Generator

Scenarios

Test

reinforce

update

System

System
Training against Random Test

Random Generator → Test Scenarios → System

reinforce

update
Training against Random Test

Random Generator

Test Scenarios

System

reinforce
update

System

reinforce
update

System
Training against Random Test

System

Random Generator

Test

Scenarios

System

reinforce

update

reinforce

update

reinforce
The Small Picture

Reinforcement Learning

Evolutionary Algorithm

system
test
Evolutionary Algorithms

Random Initialization $\rightarrow$ Selection $\rightarrow$ Result

Mutation $\rightarrow$ Recombination
Training against SCoE Test

System

Test

Reinforcement Learning

Evolutionary Algorithm
Training against SCoE Test

Random Generator → Test

System
Training against SCoE Test

Random Generator → Test

reinforce → System

update → System

reinforce → System
Training against SCoE Test

System → Random Generator

reinforce → System
update → System

evolve → Test

reinforce → Test
Training against SCoE Test

Random Generator

Test

System

reinforce

update

System

Test

evolve

System

reinforce

update

System

reinforce

update

System

reinforce
Experimental Setup

- System
- Reinforcement Learning
- SCoE Test
- Evolutionary Algorithm
- System
- Reinforcement Learning
- Random Generator
Learning Rates
Experimental Setup

System → SCoE Test → Evaluation

Reinforcement Learning
Evolutionary Algorithm
Random Generator

System → Random Test → Evaluation

Reinforcement Learning
Random Generator
Random Generator
Effective Performance
Performance over Time

The graph shows the average score over runtime (seconds) for two different scenarios: ScoE and Random. ScoE consistently outperforms Random throughout the runtime, with scores peaking and troughing around the 20,000 to 30,000 second mark. ScoE's performance is more stable and consistent compared to the fluctuations observed in Random.
Successful Runs

Number of Successful Runs: 61

Graph showing the percentage of successful tests over episodes for two different methods: random and scoe.
Generated Test Cases

![Graph showing generated test cases with scores ranging from -25000 to 0. The bars represent the amount of test cases for different score ranges, with a significant increase in the ScoE category near score 0.]
Scenario Co-Evolution as a Tool for Software Engineering
Criticality Focus
all means of generating new scenarios are continuously being explored in order to achieve sufficient coverage of the scenario space
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Criticality Focus

All means of generating new scenarios are continuously being explored in order to achieve sufficient coverage of the scenario space.
all means of generating new scenarios are continuously being explored in order to achieve sufficient coverage of the scenario space
The importance of scenarios is weighted according to inverse performance of system-under-test.

Criticality Focus

all means of generating new scenarios are continuously being explored in order to achieve sufficient coverage of the scenario space

system performance: ??

requirement

acquisition

evaluation

break down

evaluation

system performance: 42
Adaptation Cooldown

start of development
Adaptation Cooldown

- **Start of development**
  - **Off-site adaptation borders**
    - Defining the desired limits of the adaptation process for all eventual customer scenarios.
Adaptation Cooldown

start of development

off-site adaptation borders

defining the desired limits of the adaptation process for all eventual customer scenarios

scenario evolution finds faulty behavior early and brings the adaptive system to behave within the adaptation borders
Adaptation Cooldown

Start of development

Off-site adaptation borders

Defining the desired limits of the adaptation process for all eventual customer scenarios

Scenario evolution finds faulty behavior early and brings the adaptive system to behave within the adaptation borders
Adaptation Cooldown

start of development

off-site adaptation borders

defining the desired limits of the adaptation process for all eventual customer scenarios

scenario evolution finds faulty behavior early and brings the adaptive system to behave within the adaptation borders

adapting to a single customer’s specific environment changes the optimal behavior slightly
Adaptation Cooldown

start of development

off-site adaptation borders
- defining the desired limits of the adaptation process for all eventual customer scenarios

scenario evolution finds faulty behavior early and brings the adaptive system to behave within the adaptation borders

adapting to a single customer’s specific environment changes the optimal behavior slightly

running product

on-site adaptation borders
- during deployment narrower boundaries for adaptation with respect to one customer’s specific environment may be necessary
As system development progresses, the space of possible behavior available to the adaptation mechanism decreases.

- **off-site adaptation borders**: defining the desired limits of the adaptation process for all eventual customer scenarios.
- **scenario evolution**: finds faulty behavior early and brings the adaptive system to behave within the adaptation borders.
- **adapting to a single customer’s specific environment**: changes the optimal behavior slightly.
- **on-site adaptation borders**: during deployment narrower boundaries for adaptation with respect to one customer’s specific environment may be necessary.
Eternal Deployment
Eternal Deployment

Don’t deploy!
Eternal Deployment

Don’t deploy!

Deploy?
Eternal Deployment

Don’t deploy!

Deploy?

Deploy??
Eternal Deployment

Don't deploy!

Deploy?

Deploy??
Eternal Deployment

system-under-tests immediately adapts to scenario evolution
Eternal Deployment

Don't deploy!

Deploy?

Deploy??

system-under-tests immediately adapts to scenario evolution
Eternal Deployment

Don’t deploy!

Deploy?

Deploy??

system-under-tests immediately adapts to scenario evolution

(more) independent line of scenarios with no immediate feedback for the system-under-test
Eternal Deployment

Don’t deploy!

system-under-tests immediately adapts to scenario evolution

Deploy?

(more) independent line of scenarios with no immediate feedback for the system-under-test

Deploy??

Deploy All

Trustworthiness is aided by deploying all tests so they can be repeated at the customer’s site.

As system development progresses, the space of possible behavior available to the adaptation mechanism decreases.

Criticality Focus

The importance of scenarios is weighted according to inverse performance of system-under-test.

Deploy All

Trustworthiness is aided by deploying all tests so they can be repeated at the customer’s site.
The Big Picture

Software Architecture

Software Gardening?

88
We need AI to adequately control AI.
Where to go from here?
Where to go from here?

adaptation

even better system

is tested by

is used for training

adaptation

even better test

is tested by

is used for training
Where to go from here?

Generalization of this 1v1 setting to a **multi-agent system** with various (degrees of) adversaries.

“Penguin recombination” specifically designed for tests with sequential execution steps.

Quantifying and detecting uncertainty in new situations

Explicit **curriculum learning** for “gentle introduction” of requirements according to specification into reward.

Construction of **whole test suites** based on diversity and/or incremental complexity.
1) “AI researchers have often tried to build knowledge into their agents,

2) this always helps in the short term, and is personally satisfying to the researcher, but

3) in the long run it plateaus and even inhibits further progress, and

4) breakthrough progress eventually arrives by an opposing approach based on scaling computation by search and learning.”
1) “AI researchers have often tried to build knowledge into their agents,
2) this always helps in the short term, and is personally satisfying to the researcher, but
3) in the long run it plateaus and even inhibits further progress, and
4) breakthrough progress eventually arrives by an opposing approach based on scaling computation by search and learning.”

“The biggest lesson that can be read from 70 years of AI research is that general methods that leverage computation are ultimately the most effective, and by a large margin.”

Computation Power used in AI

Dario Amodei and Danny Hernandez. 
AI and Compute. 
openai.com/blog/ai-and-compute/
“Since 2012, the amount of compute used in the largest AI training runs has been increasing exponentially with a 3.5 month doubling time (by comparison, Moore’s Law had an 18 month doubling period).”
Options for the Future

AI experiments become more expensive

Progress in AI research slows down

We find a way to increase available computing power
Options for the Future

- AI experiments become more expensive
- Progress in AI research slows down
- We find a way to increase available computing power
Options for the Future

- AI experiments become more expensive
- Progress in AI research slows down
- We find a way to increase available computing power
An Awful Lot of Expertise

Domain Analysis

AI Algorithms

Quantum Platform
The PlanQK Platform

QAI algorithms

Implementation

Analysis Standardization

QAI concepts

developers

specialists community

The PlanQK consortium. planqk.de
The PlanQK Platform

QAI concepts

QAI algorithms

QAI applications

Search & Order

Implementation

Analysis Standardization

users

developers

specialists community

The PlanQK consortium. planqk.de
The PlanQK Platform

- QAI concepts
- QAI algorithms
- QAI applications
- packaged solution

Analysis
Standardization
Implementation
Search & Order

users
developers
specialists community

The PlanQK consortium. planqk.de
So what else is new?

Quantum Computing

- superposition
- entanglement
Superposition

classical physics

particle
Superposition

classical physics

particle

spin
Superposition

particle

spin

measure spin

classical physics
Superposition

- particle
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- measure spin
- measured spin

classical physics
Superposition

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quantum physics
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Superposition

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quantum physics

particle

spin

measure spin

measured spin
Superposition

classical physics

particle
spin
measure spin
measured spin
changed particle

quantum physics
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Registers
Registers

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1 1 1 1 1 1 1 1 1

ASCII letter A
Superposition on Registers

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all ASCII letters at the same time
Superposition on Registers

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all ASCII letters at the same time

measuring
Superposition on Registers

all ASCII letters at the same time

measuring

ASCII letter E with probability 1/256
Superposition on Registers

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all ASCII letters at the same time

measuring

ASCII letter & with probability $1/256$
Superposition on Registers

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all ASCII letters at the same time (but probably E)

measuring

ASCII letter E with probability 0.43
Entanglement

multiple quantum particles

measure single spin

measured spin

changed particles
Entanglement

multiple quantum particles

measure single spin

measured spin

changed particles
Entanglement

multiple quantum particles

measure single spin

measured spin

changed particles
Entanglement

multiple quantum particles

measure single spin

measured spin

changed particles
Entanglement

multiple quantum particles

measure single spin

measured spin

changed particles
Entanglement

multiple quantum particles

measure single spin

measured spin

changed particles

entangled
Entanglement on Registers

ASCII letters @ A B C at the same time measuring

ASCII letter A with probability 1/4
Entanglement on Registers

ASCII letters A B at the same time

measuring

ASCII letter A with probability 1/2
## Gate Model

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**CNOT**
Gate Model

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Gate Model

At the end measure qubits
Gate Model

▸ direct pathway to universal quantum computer

▸ similar architecture to classical computers

▸ only prototypes in laboratories

▸ currently < 100 qubits
Annealing
Annealing
Annealing
Annealing

adiabatic quantum computing

add constraints infinitely slowly while adding no energy

139
Annealing

practical quantum annealing

add constraints quite slowly while adding almost no energy

constraint
Annealing

Add constraints quite slowly while adding almost no energy.

At the end, measure qubits.

Solution to constraints.
Annealing

- potentially equally powerful
- architecture built for optimization
- available commercially
- currently > 2000 qubits
Bringing it all together...
all these currently relevant *buzzwords* are…

- derived from irreversible computation
- based on probabilistic processes
- to some extent compatible…?
Main References


Image Sources

- https://www.boredpanda.com/jumping-cats/
- https://www.medicalnewstoday.com/articles/320289.php#carry_message