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

Complex Adaptive Systems

Complexity

Dynamicity

Trust

The Big Picture

preserve initial consistency throughout development

Complex Adaptive Systems

Complexity

Dynamicity

Trust

The Big Picture

Software Architecture

preserve initial consistency throughout development

Complex Adaptive Systems

Complexity

Dynamicity

Trust

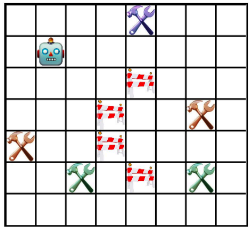
continously (re-)establish (partial) consistency from initial inconsistency

The Big Picture

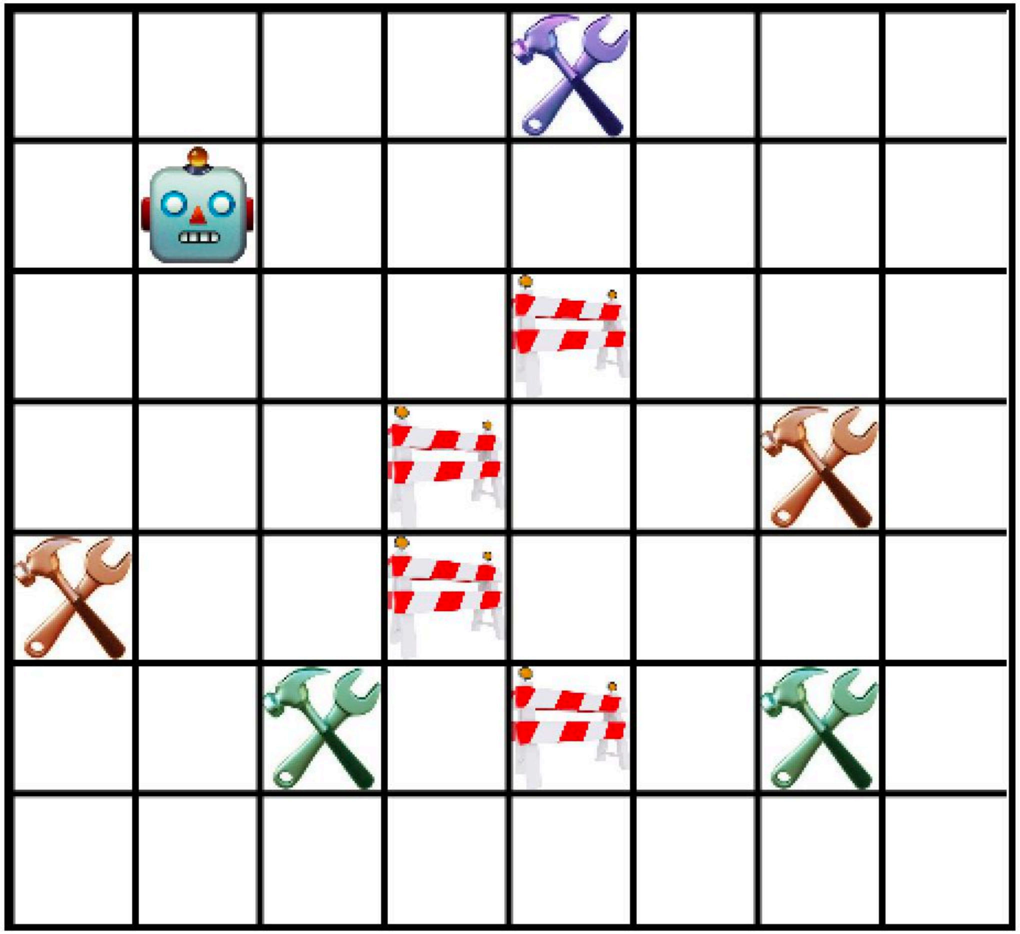
preserve initial consistency throughout development

continously (re-)establish (partial) consistency from initial inconsistency

The Small Picture

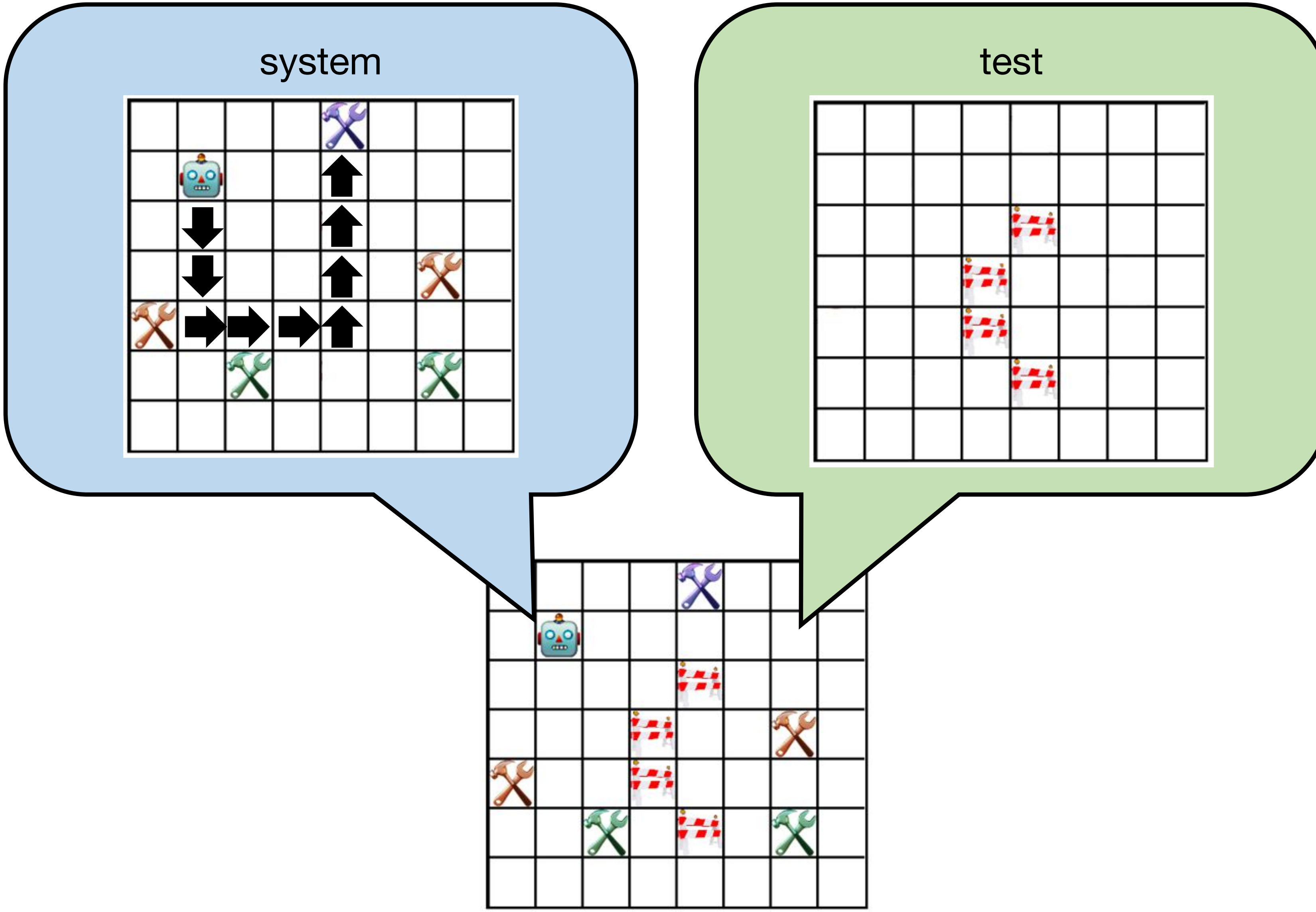


The Small Picture

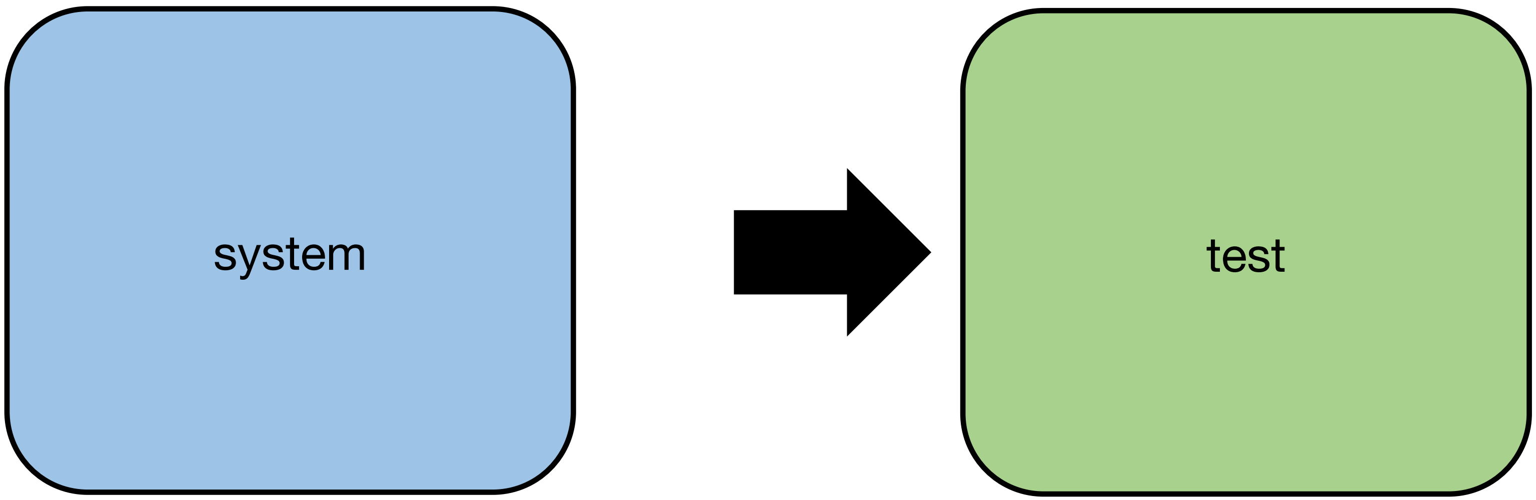


- robot starts top left
- must visit workstations of specific colors in specific order
- must not collide with obstacles
- should choose the shortest path

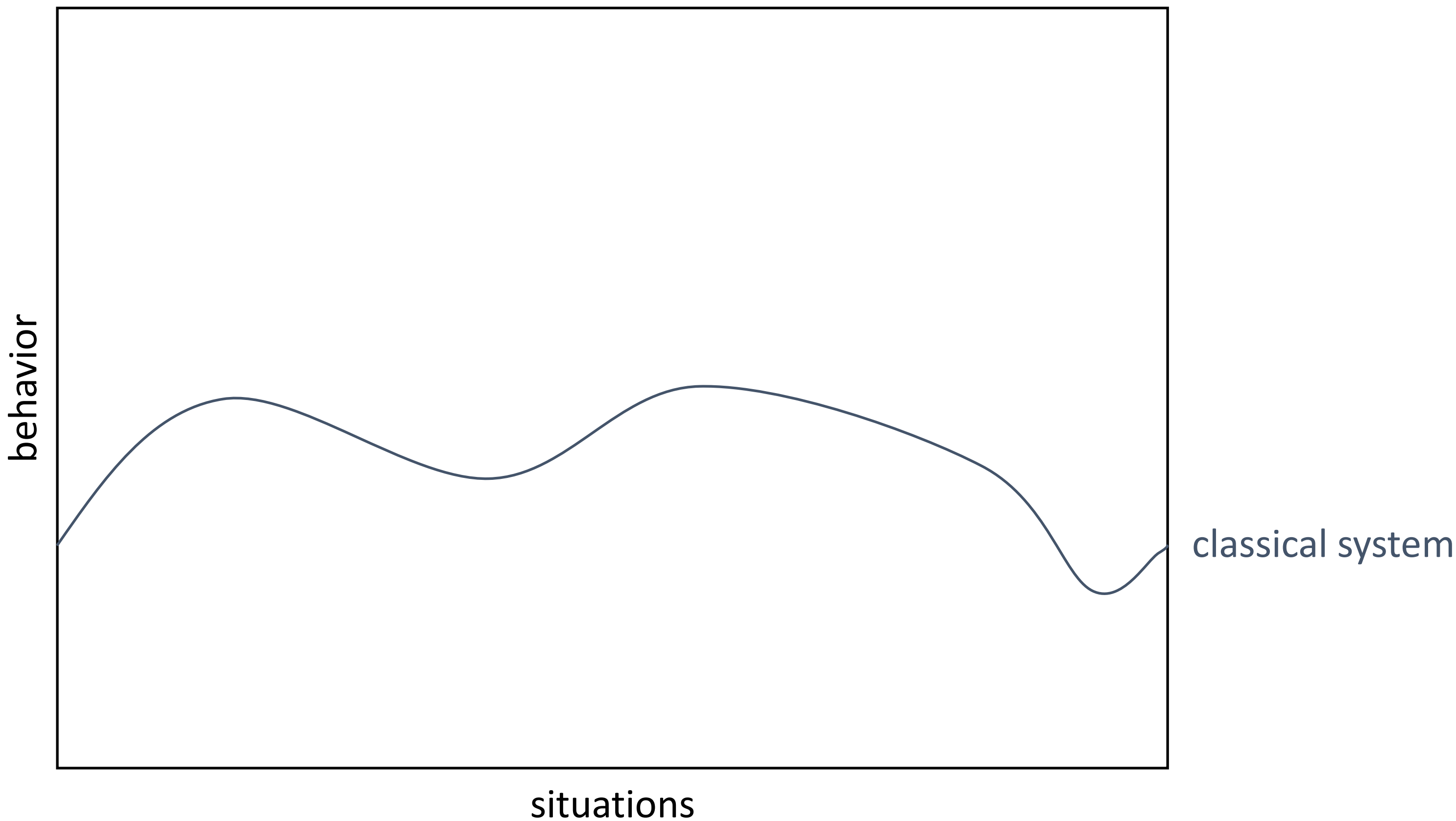
The Small Picture



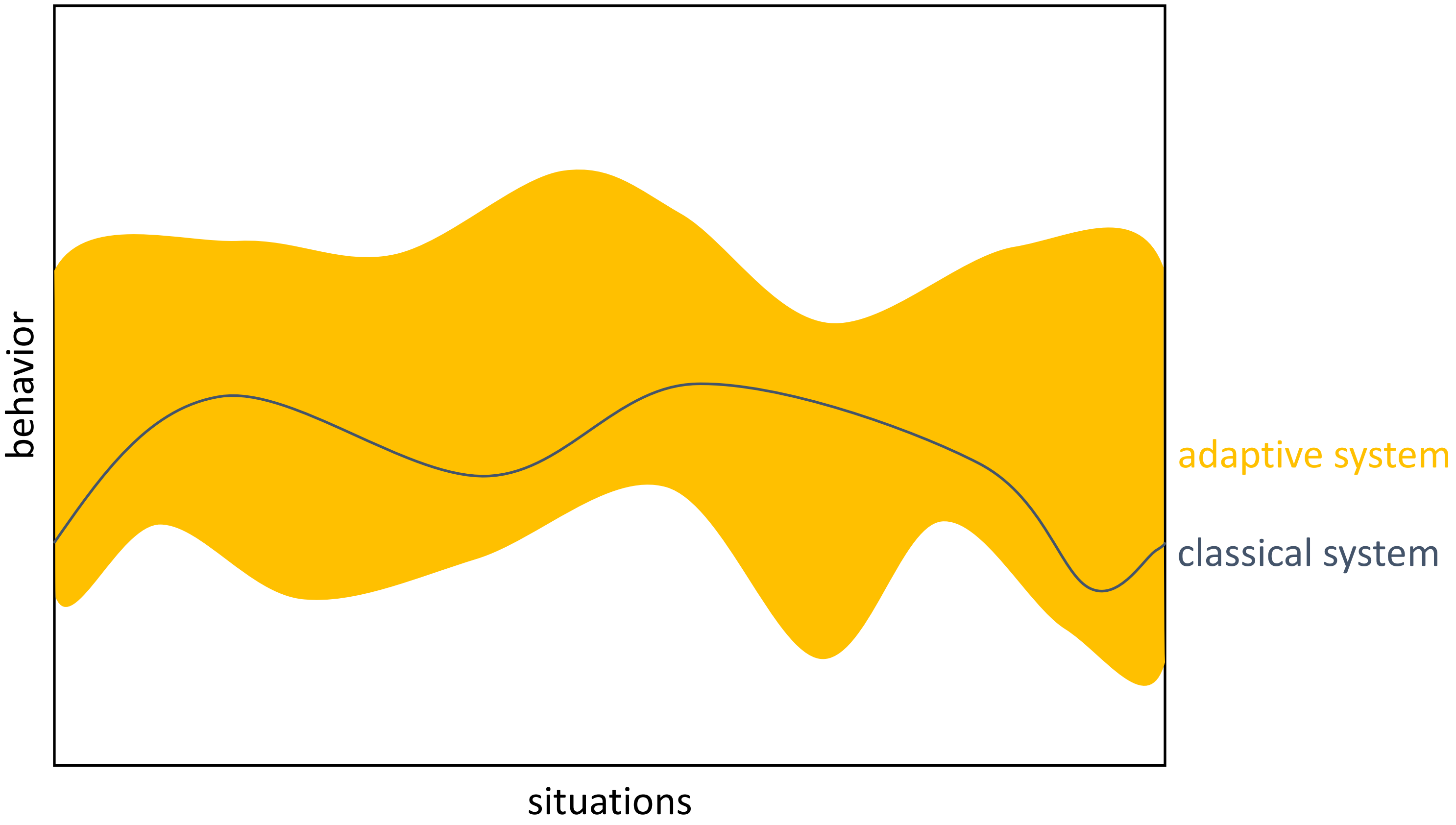
System and Test



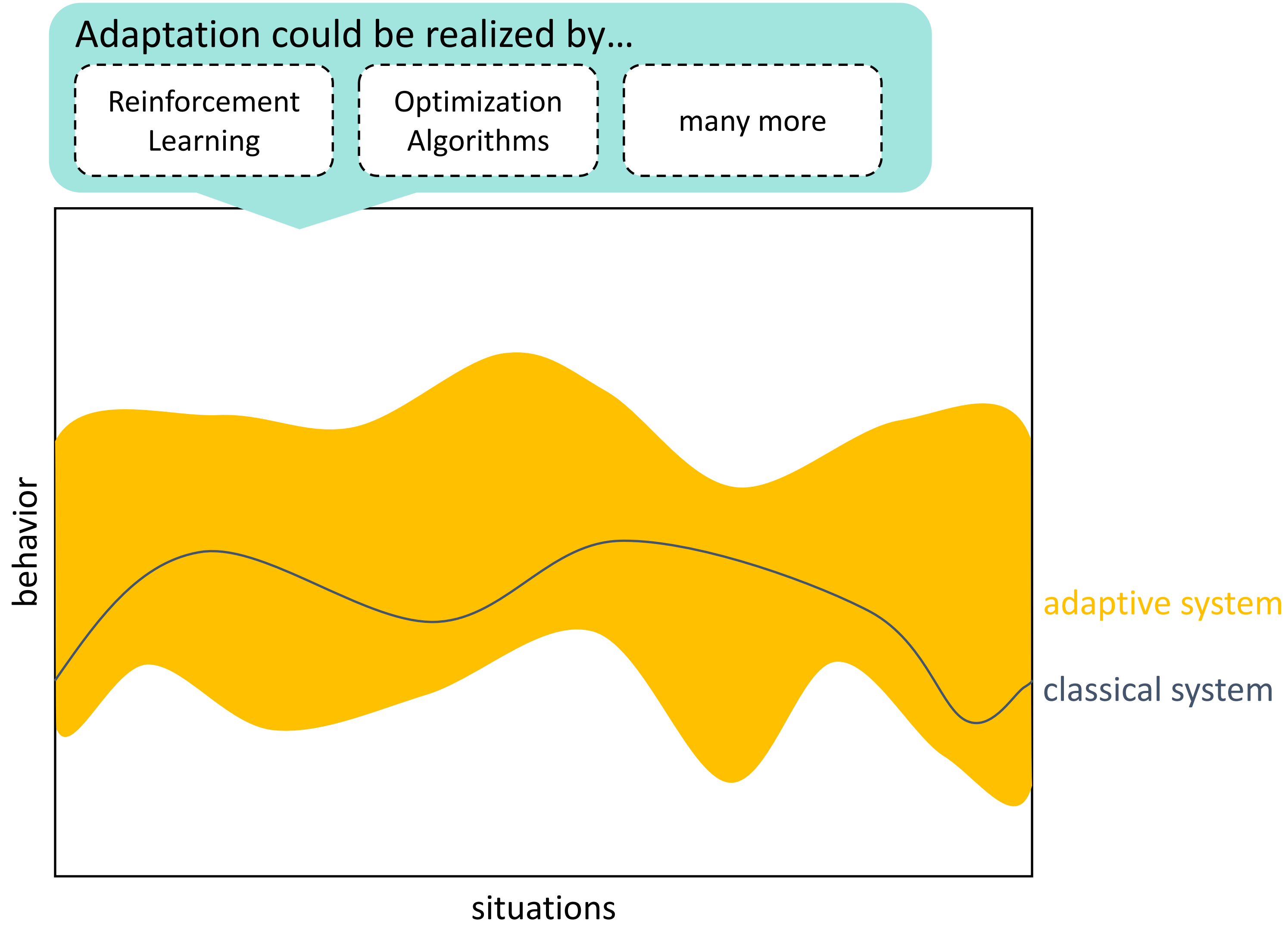
Systems



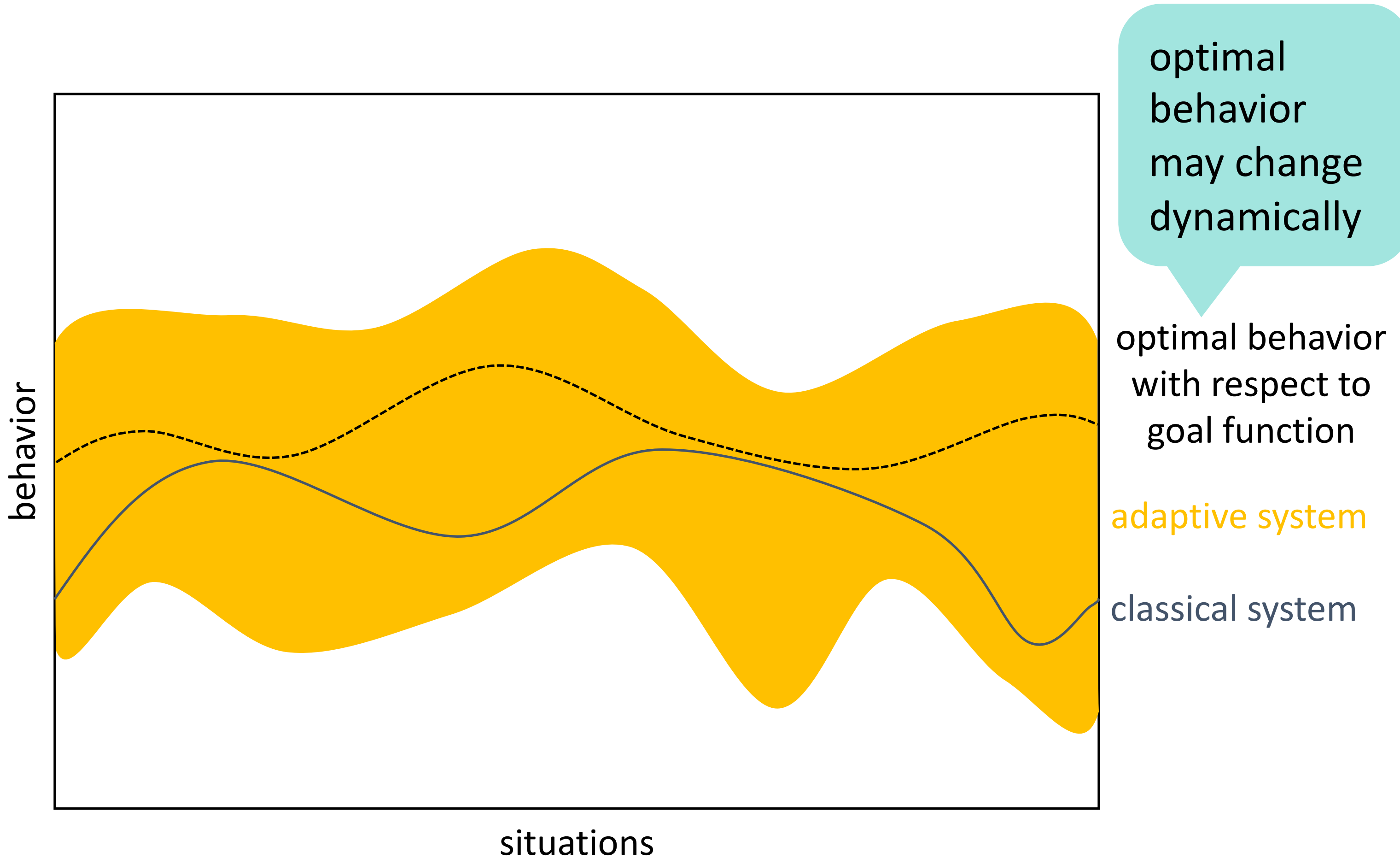
Adaptive Systems



Adaptive Systems

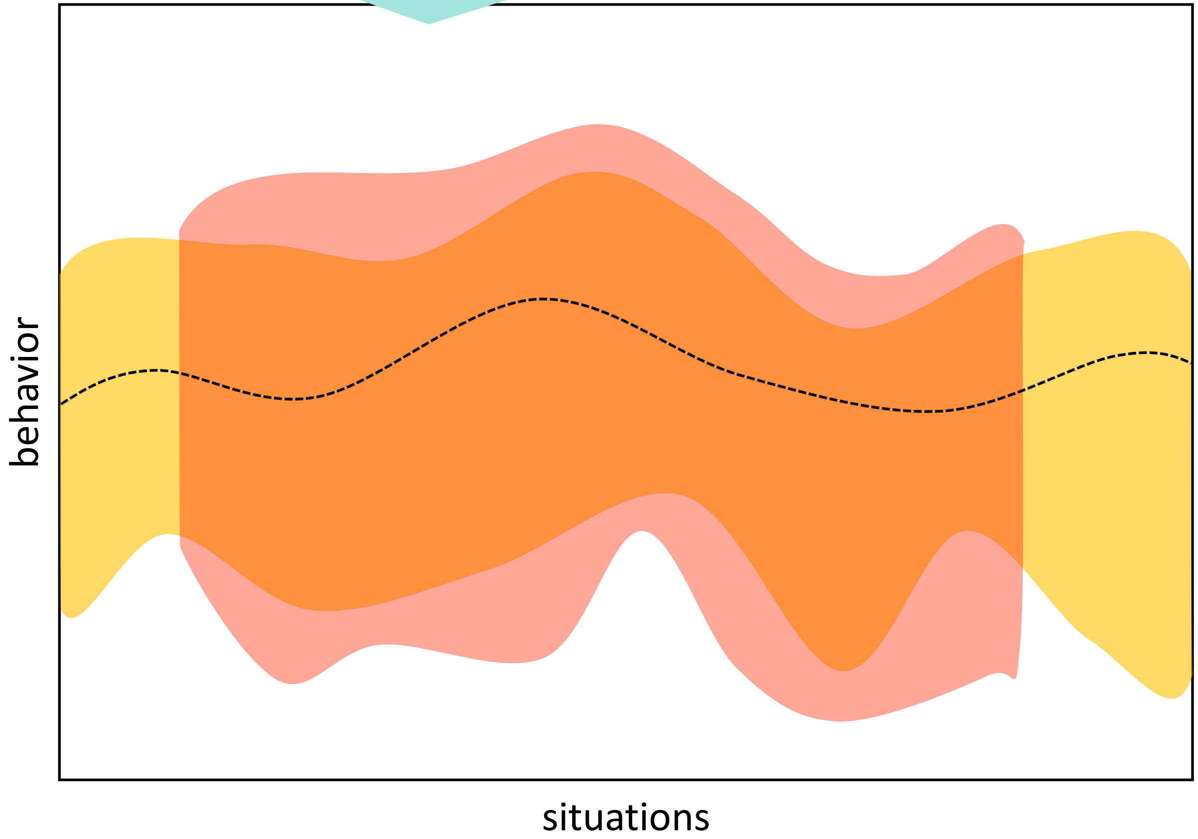


Optimizing Adaptive Systems

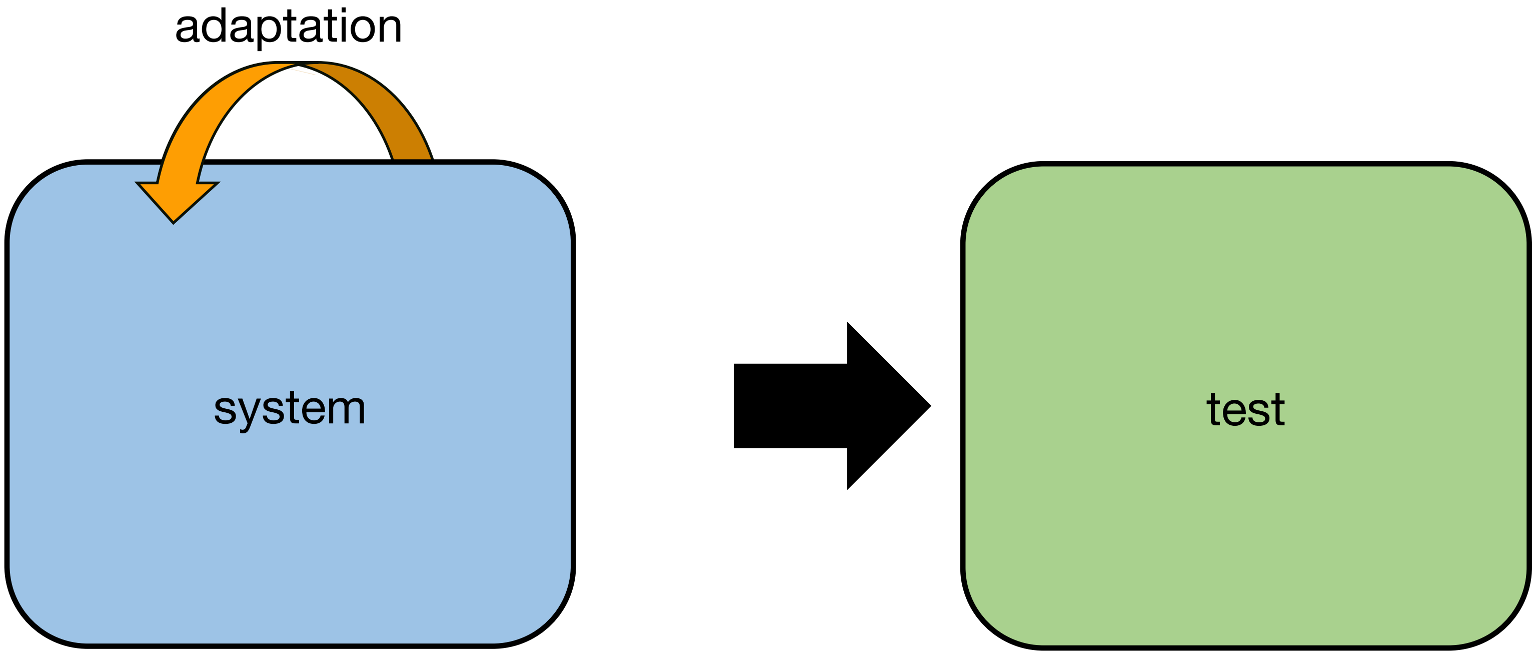


More Adaptive Systems?

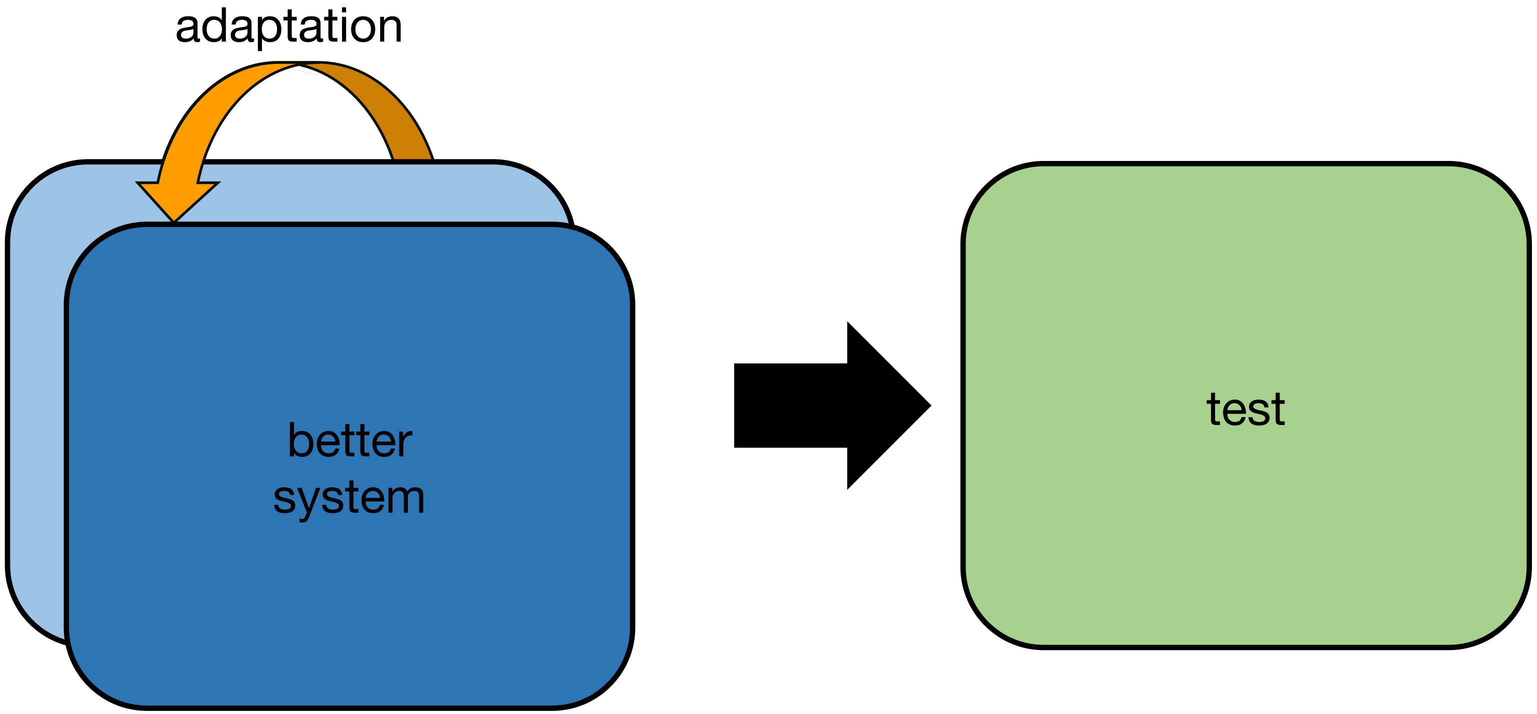
Orange is at least as adaptive as Red
<=> Orange can solve at least the situations Red can solve
AND Orange performs at least as close to the optimum as Red



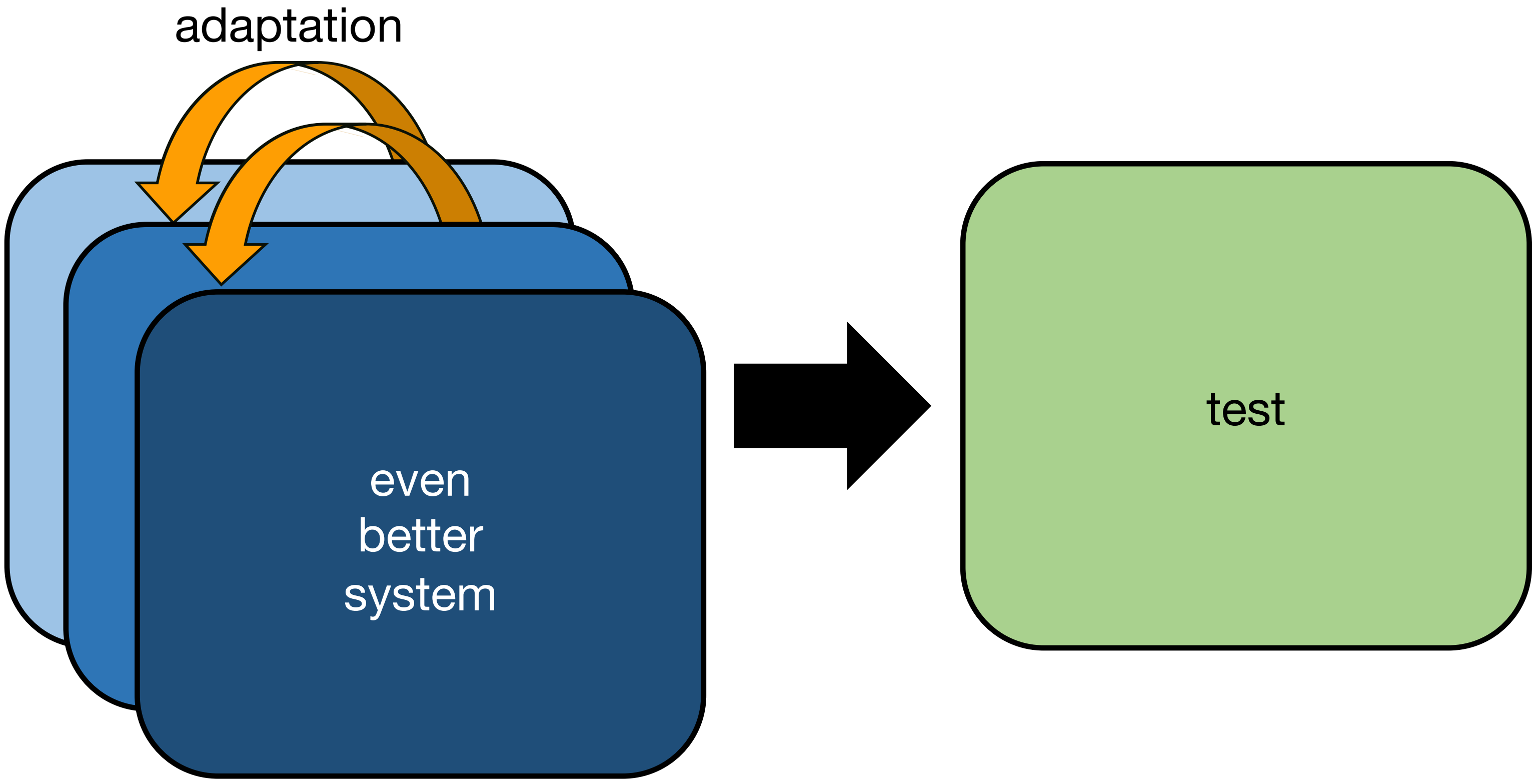
System and Test



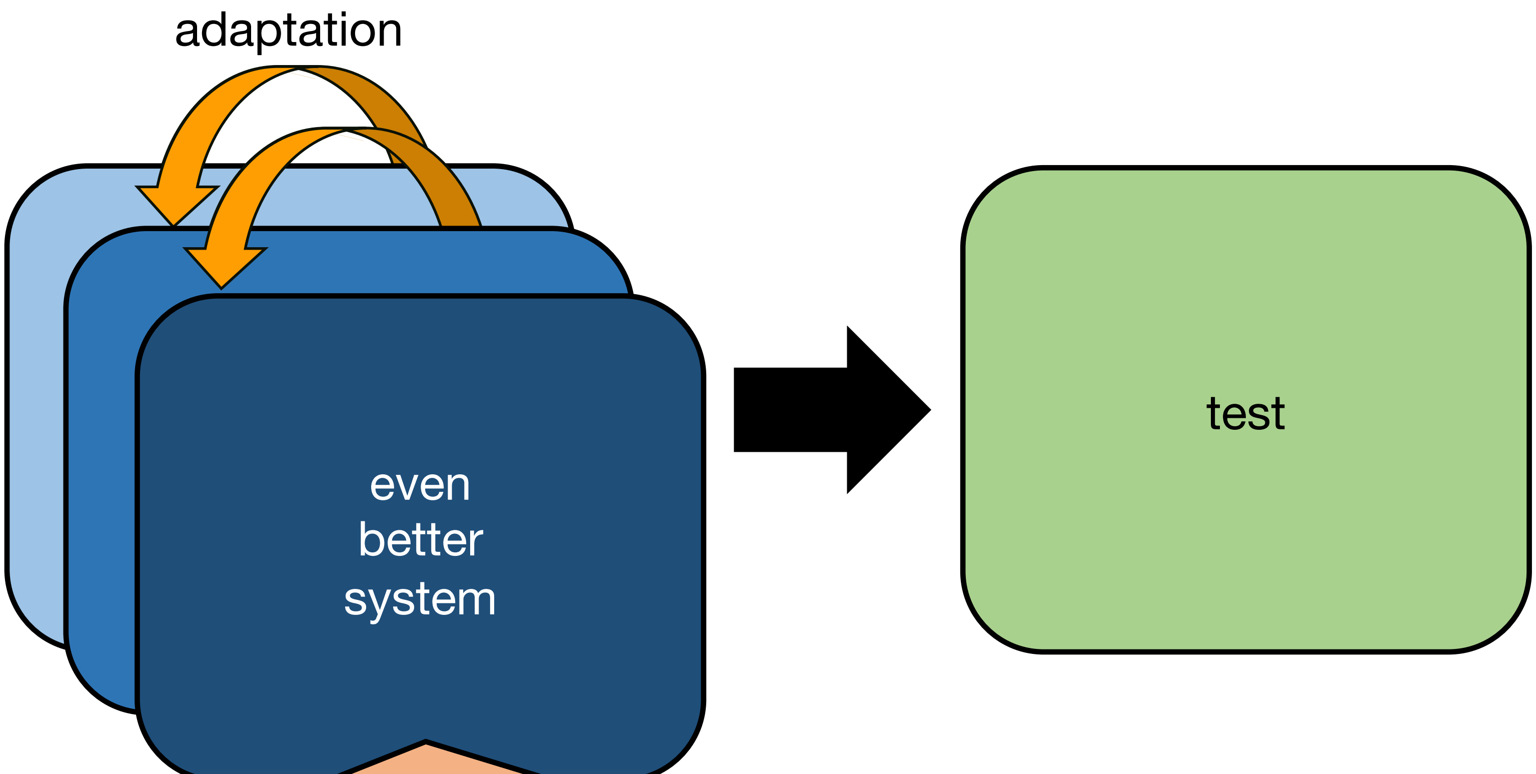
System and Test



System and Test

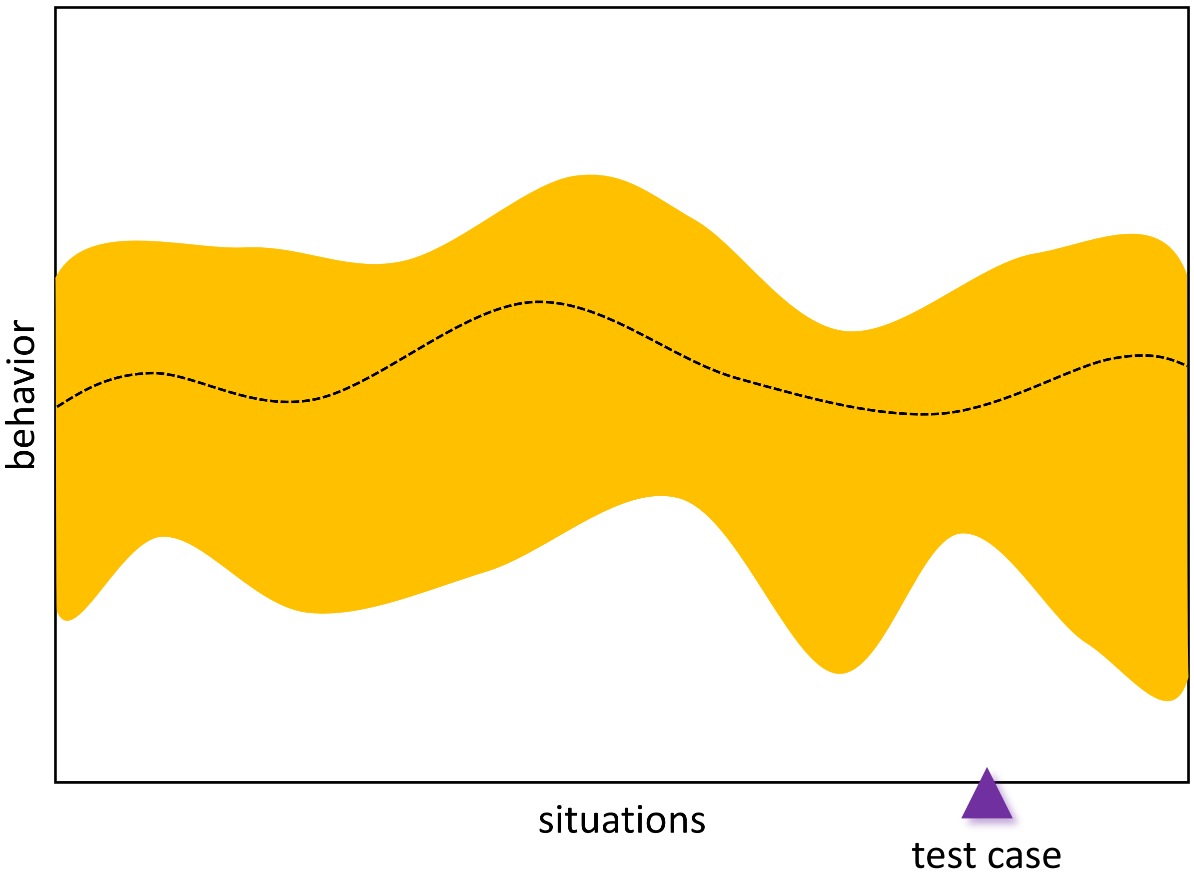


System and Test

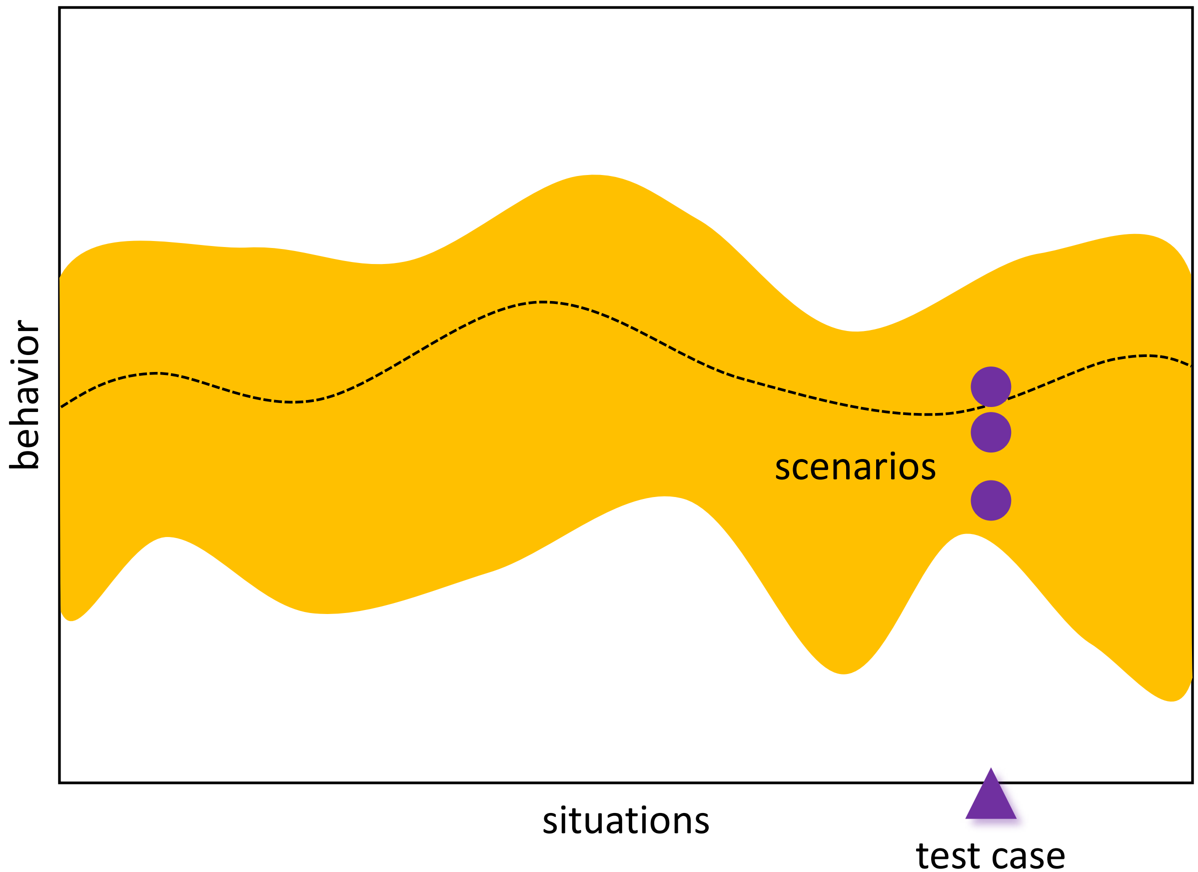


Dieselgate problem
If an adaptive system is much more powerful than its test,
then it may prefer tricking the test to solving its actual objective.

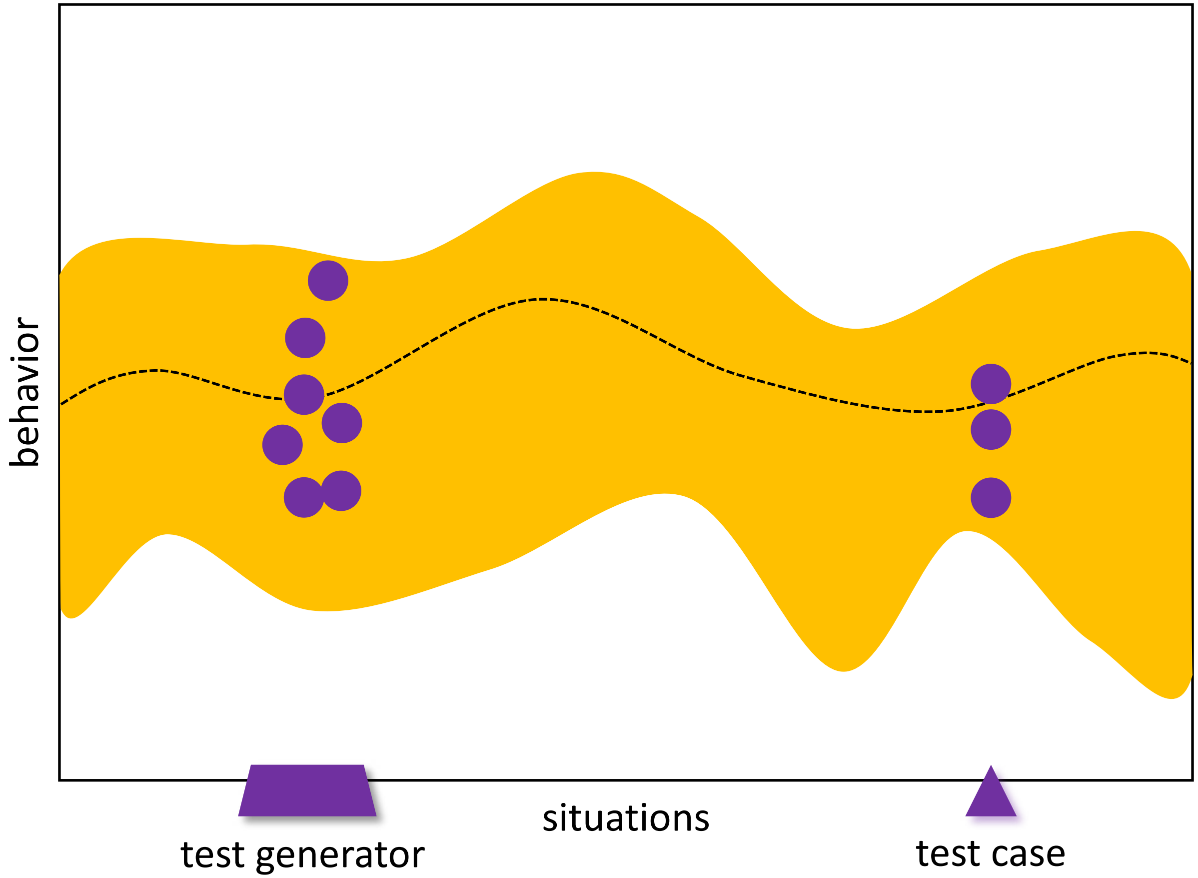
Tests



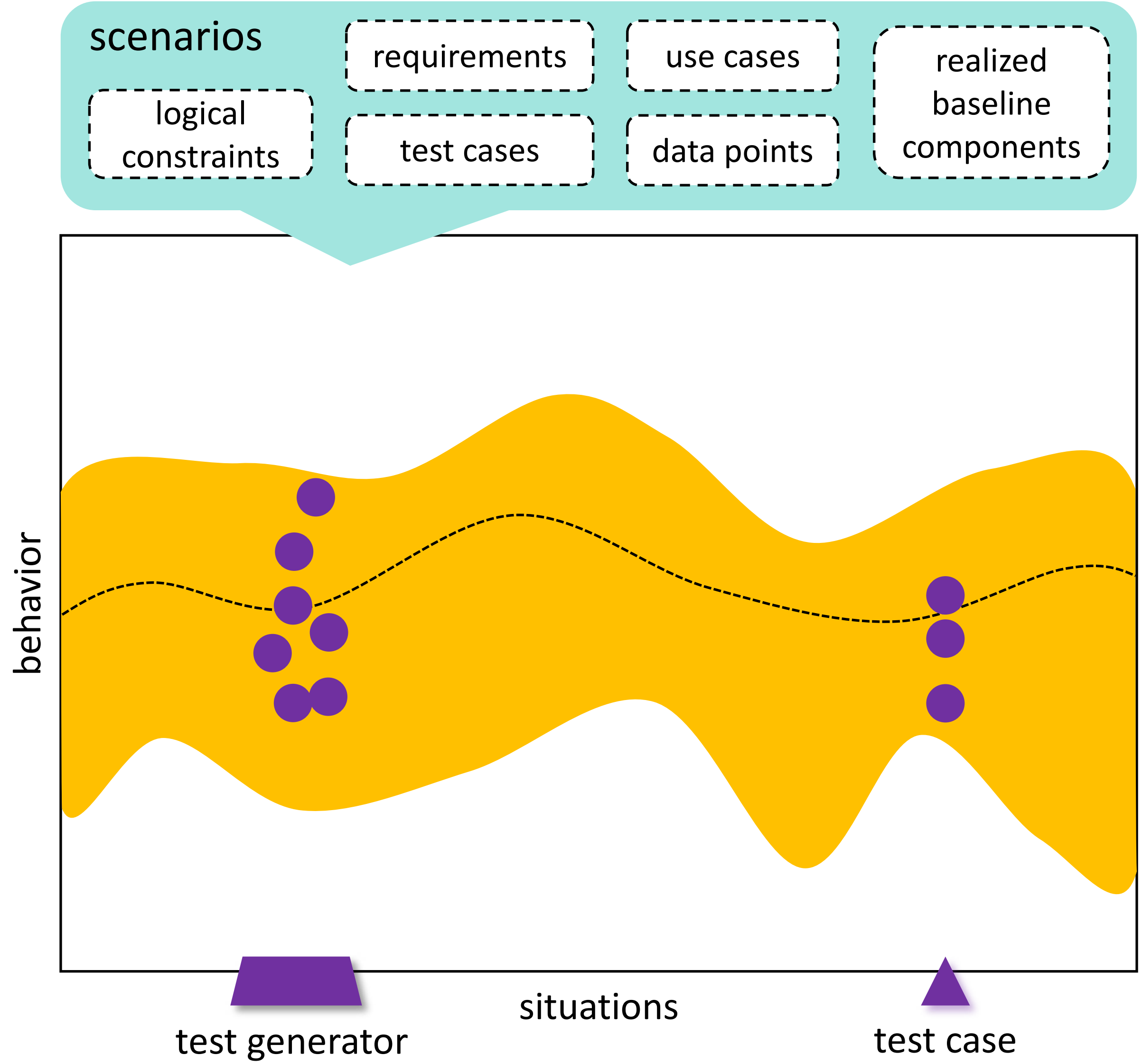
Tests of Adaptive Systems



Tests of Adaptive Systems

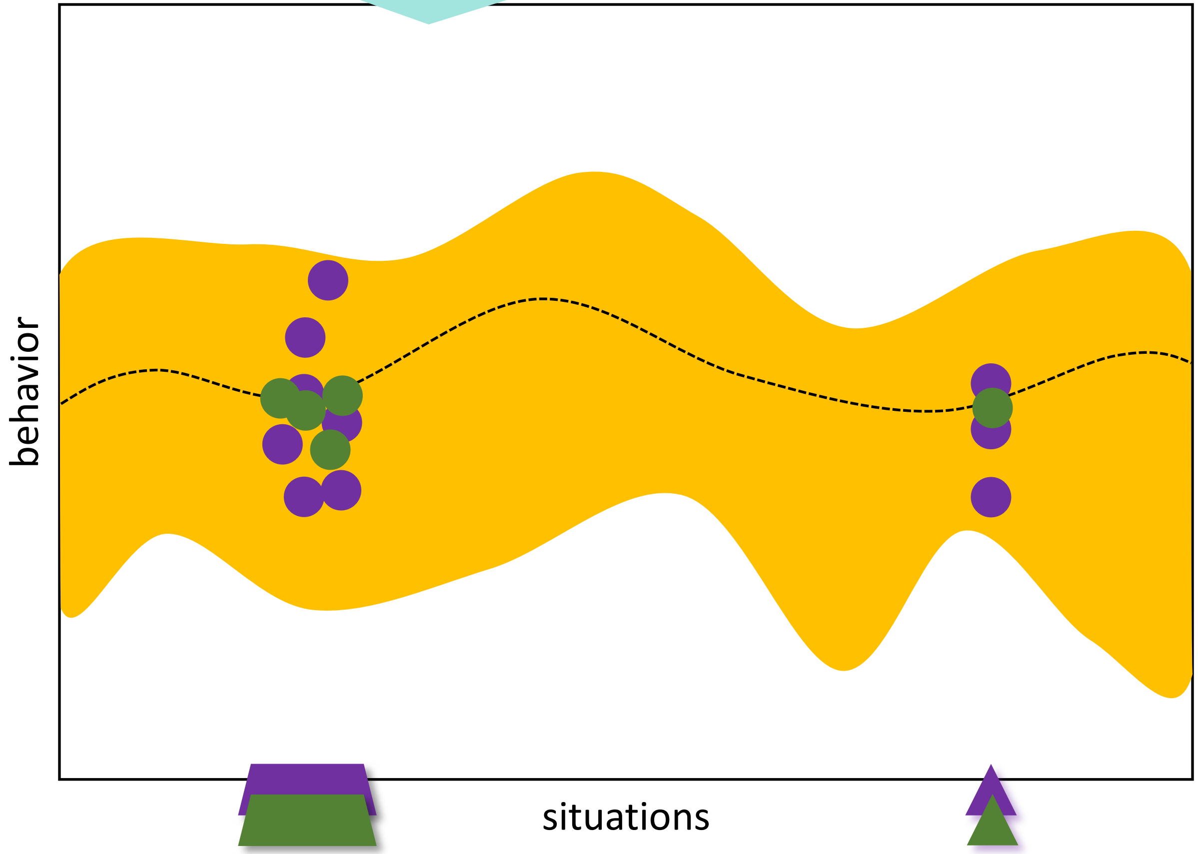


Tests of Adaptive Systems

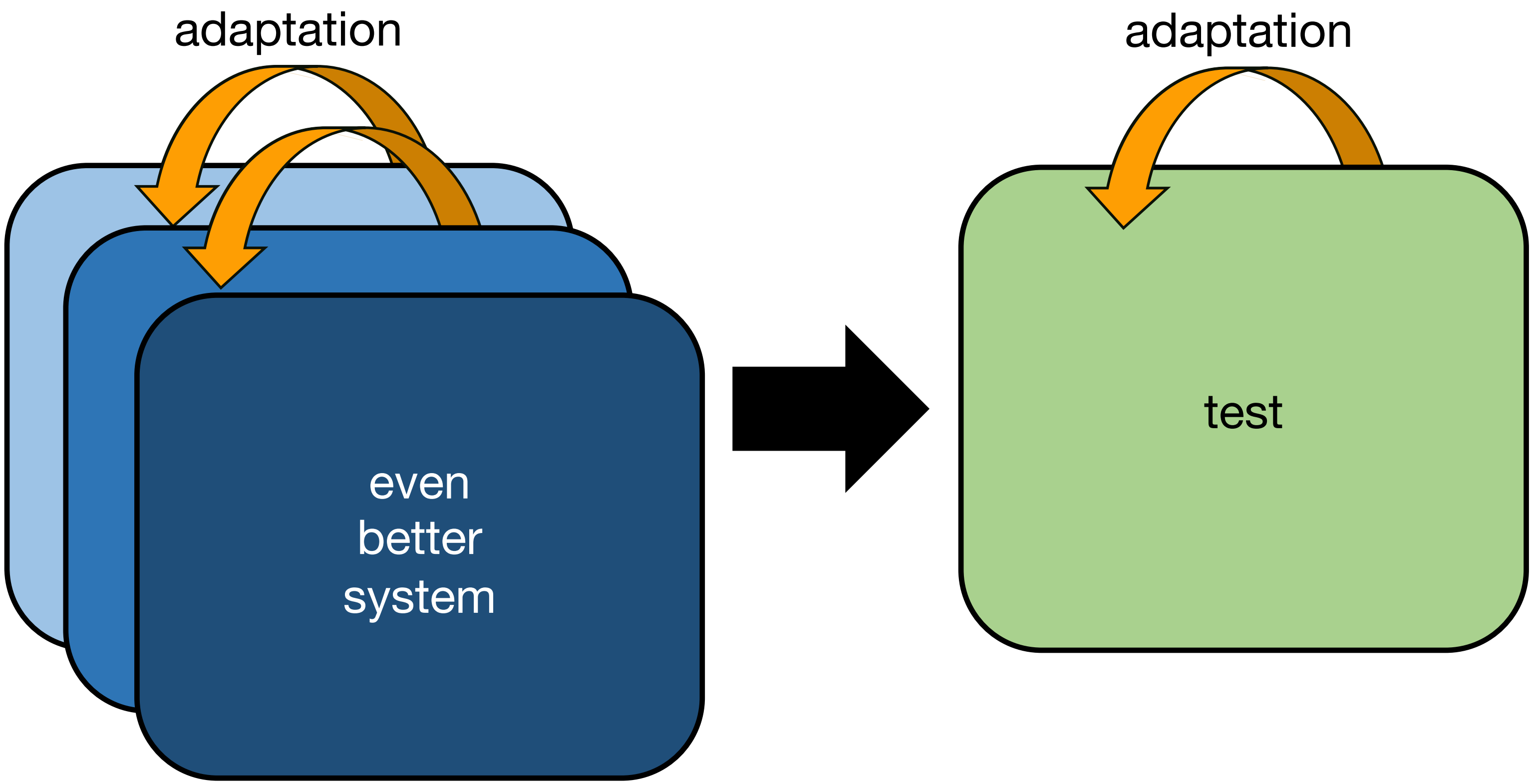


Harder Tests?

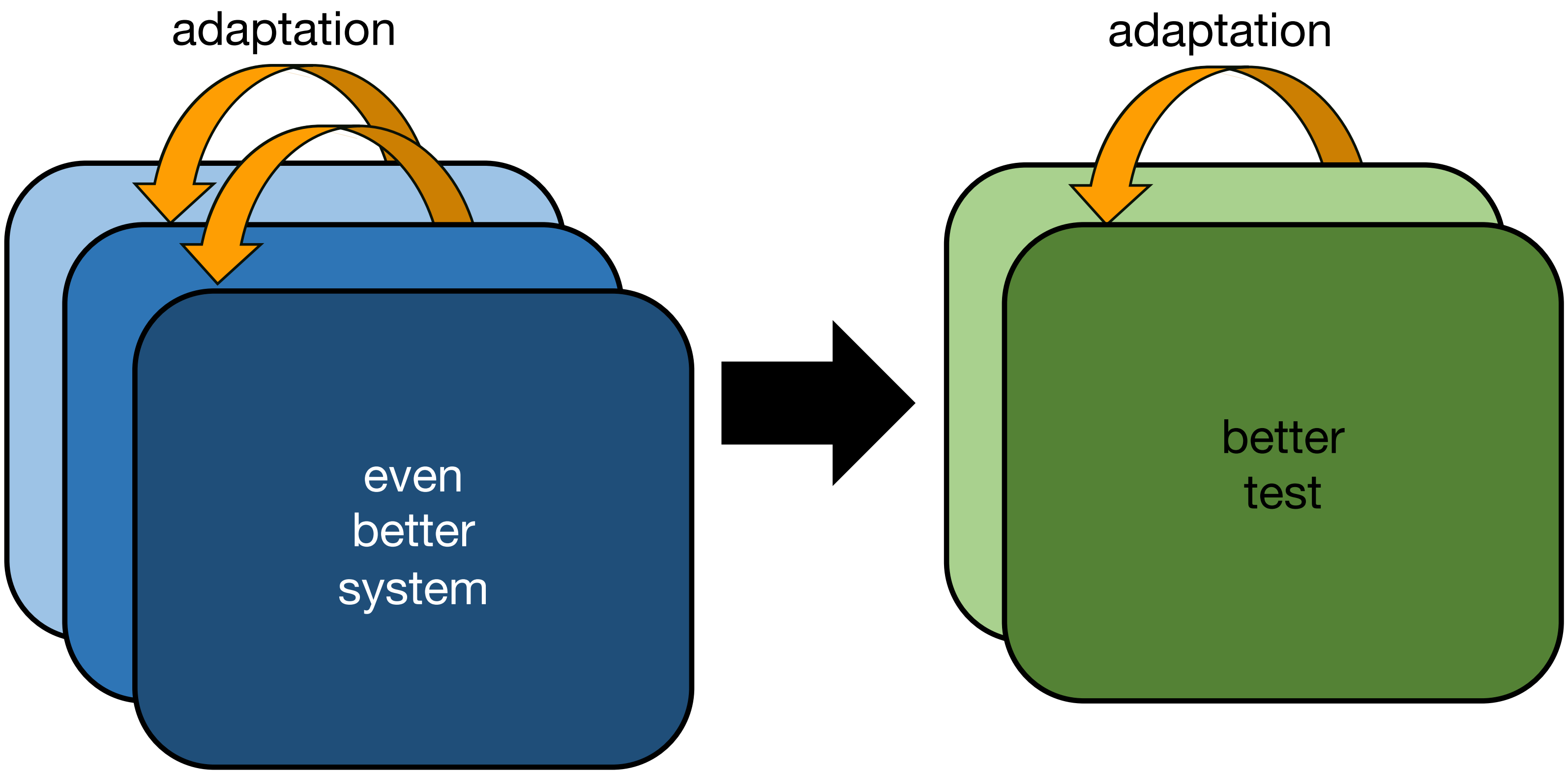
Green is at least as hard as Purple
<=> For every scenario generated by Purple, Green generates a scenario that is at least as close to optimal behavior.



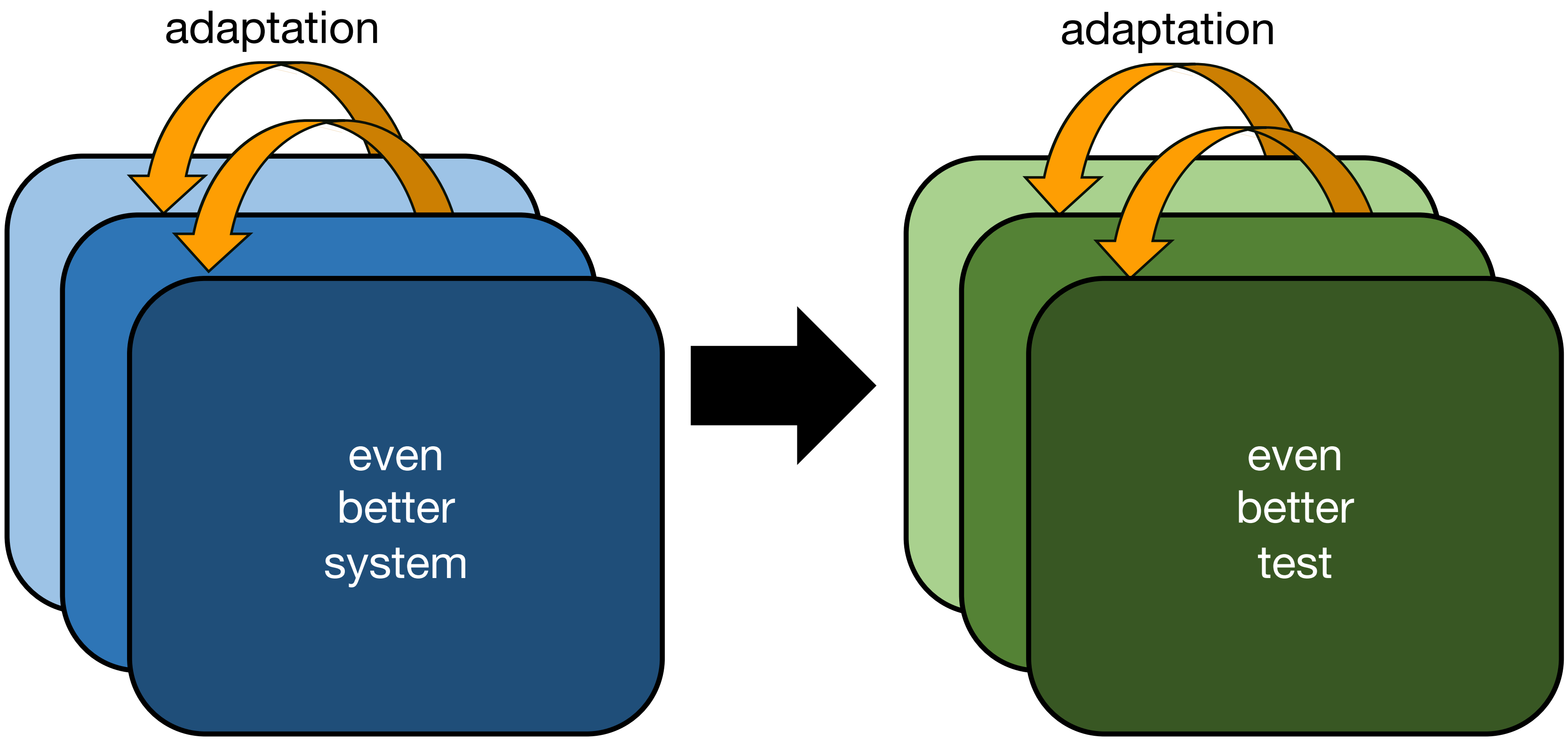
System and Test



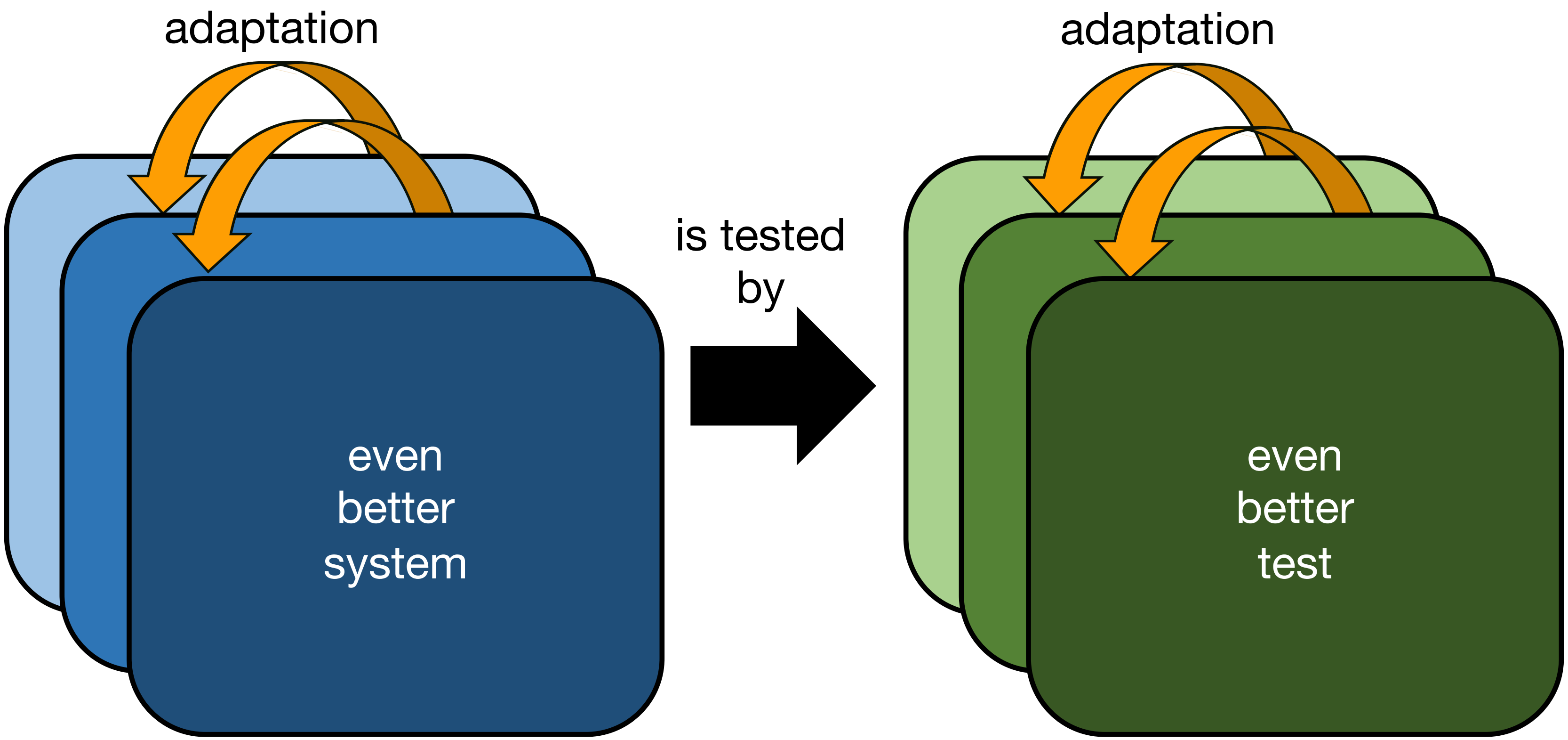
System and Test



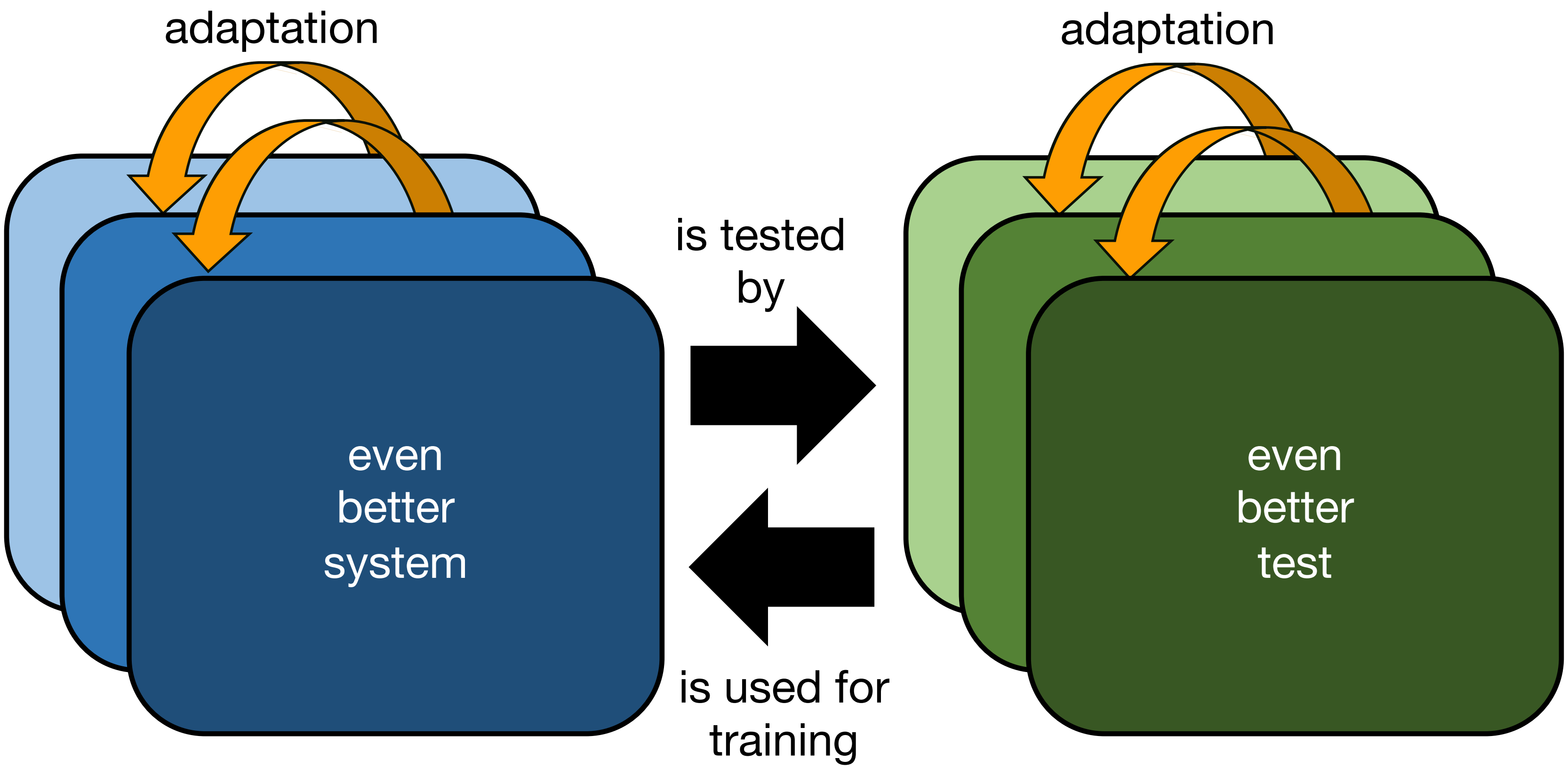
System and Test



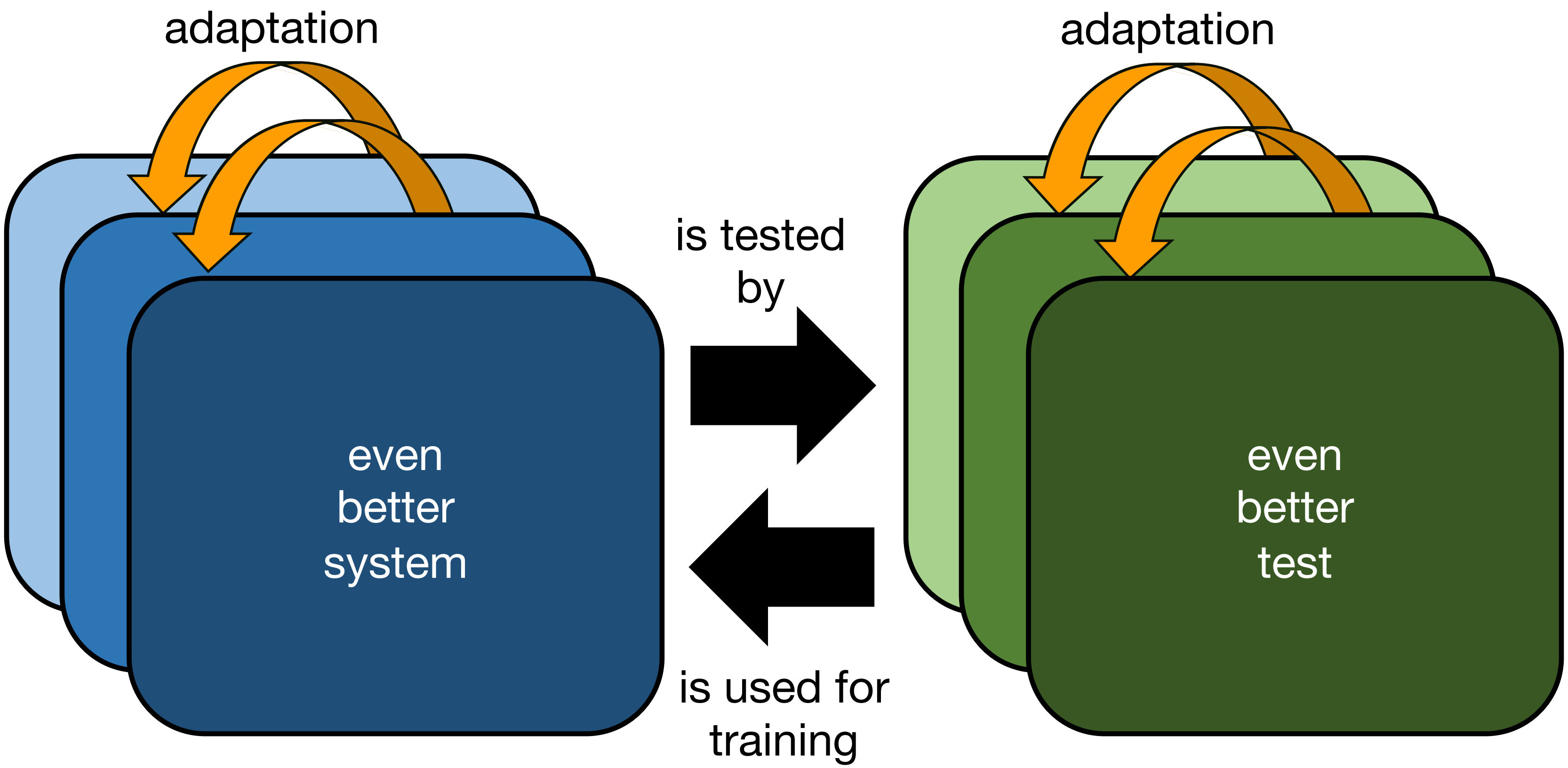
System and Test



System and Test

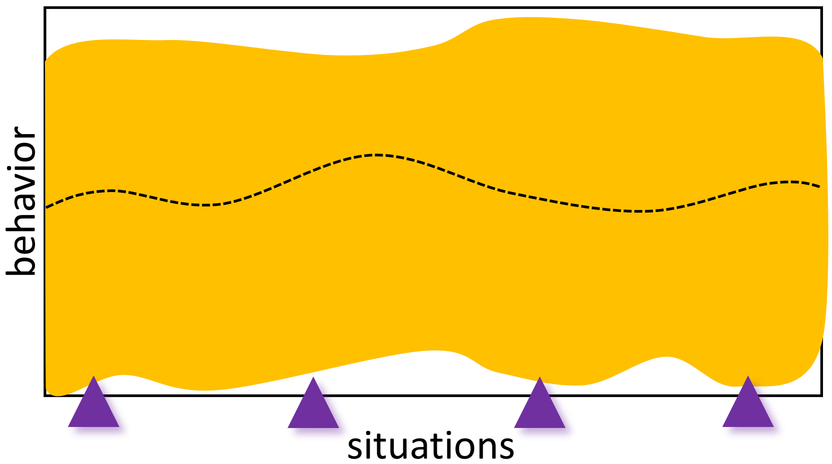


System and Test

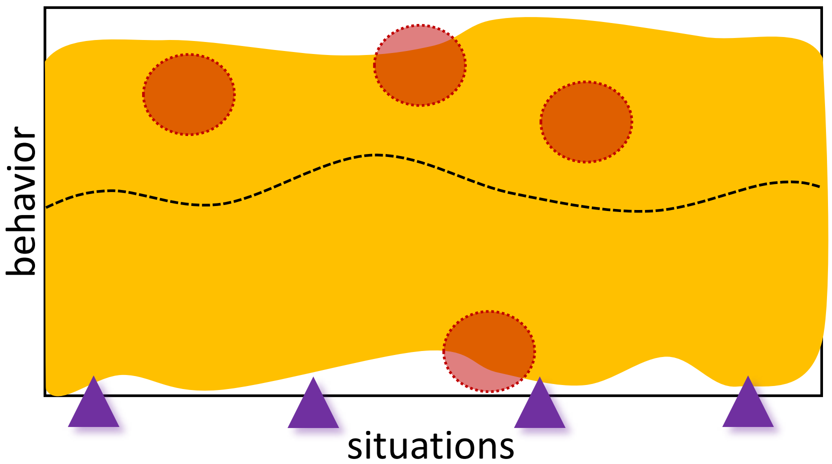


arms race between system and test
Scenario Co-Evolution

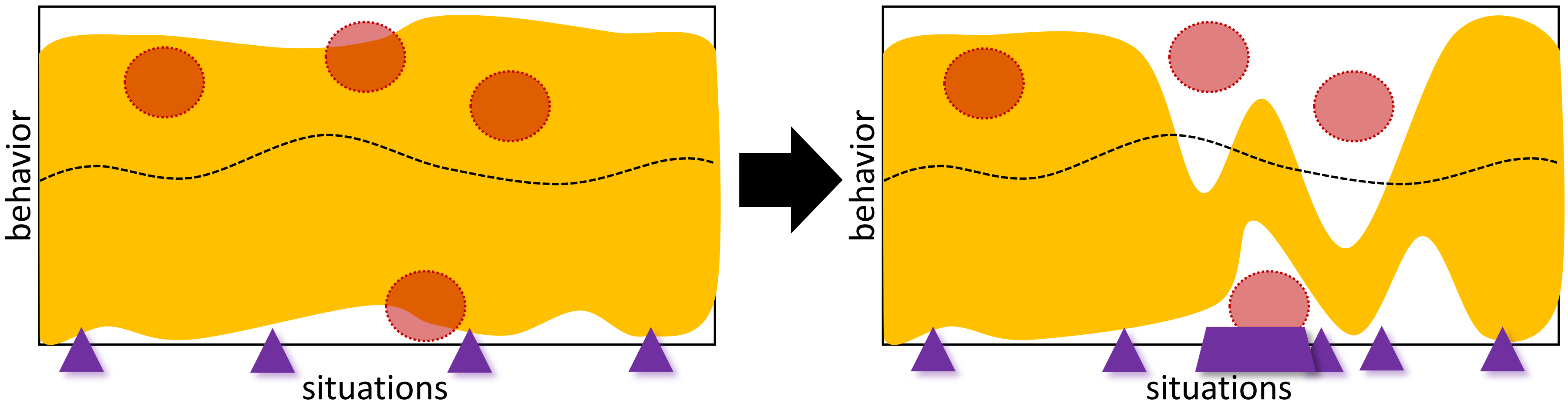
Coevolution



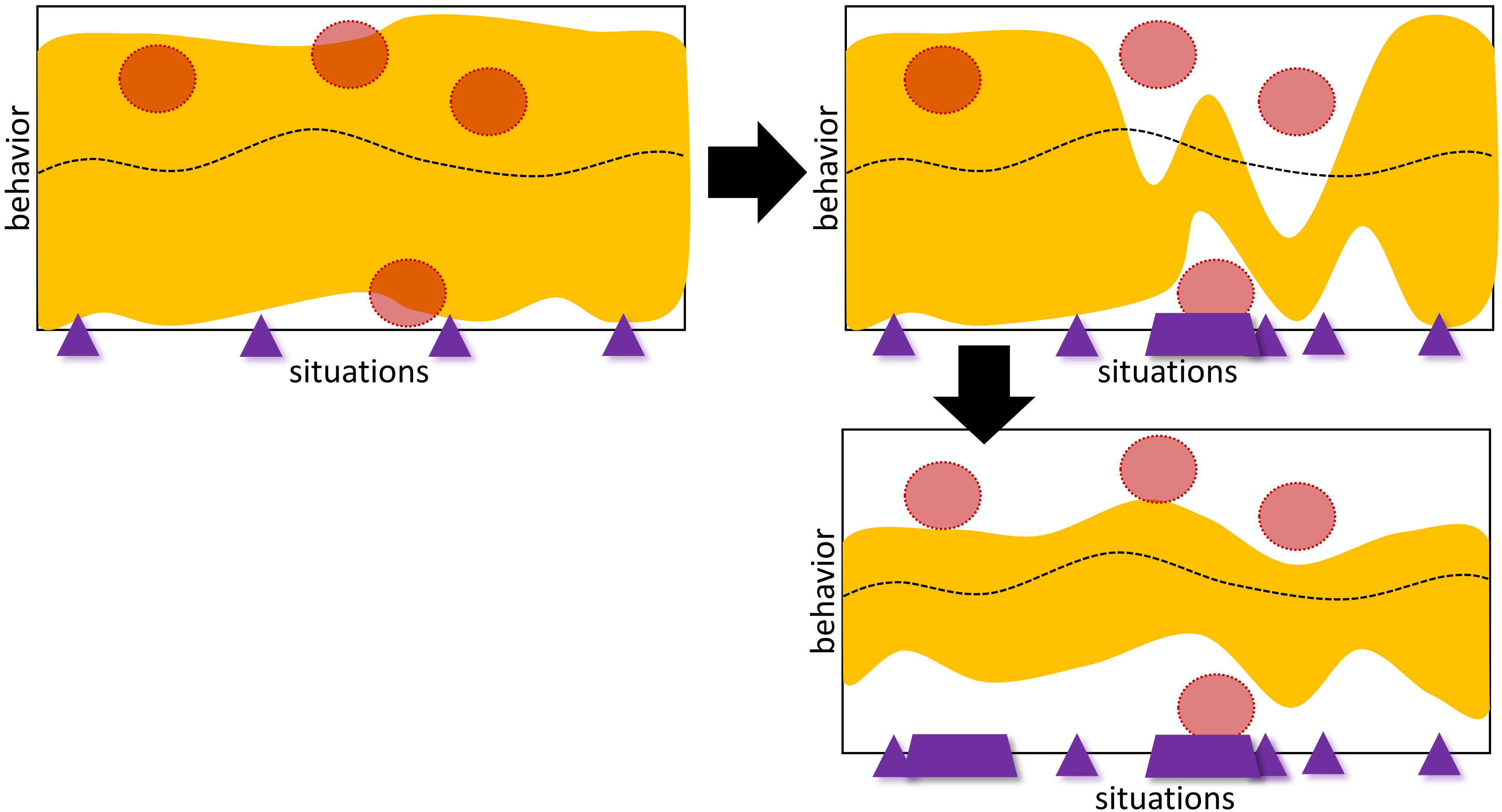
Coevolution



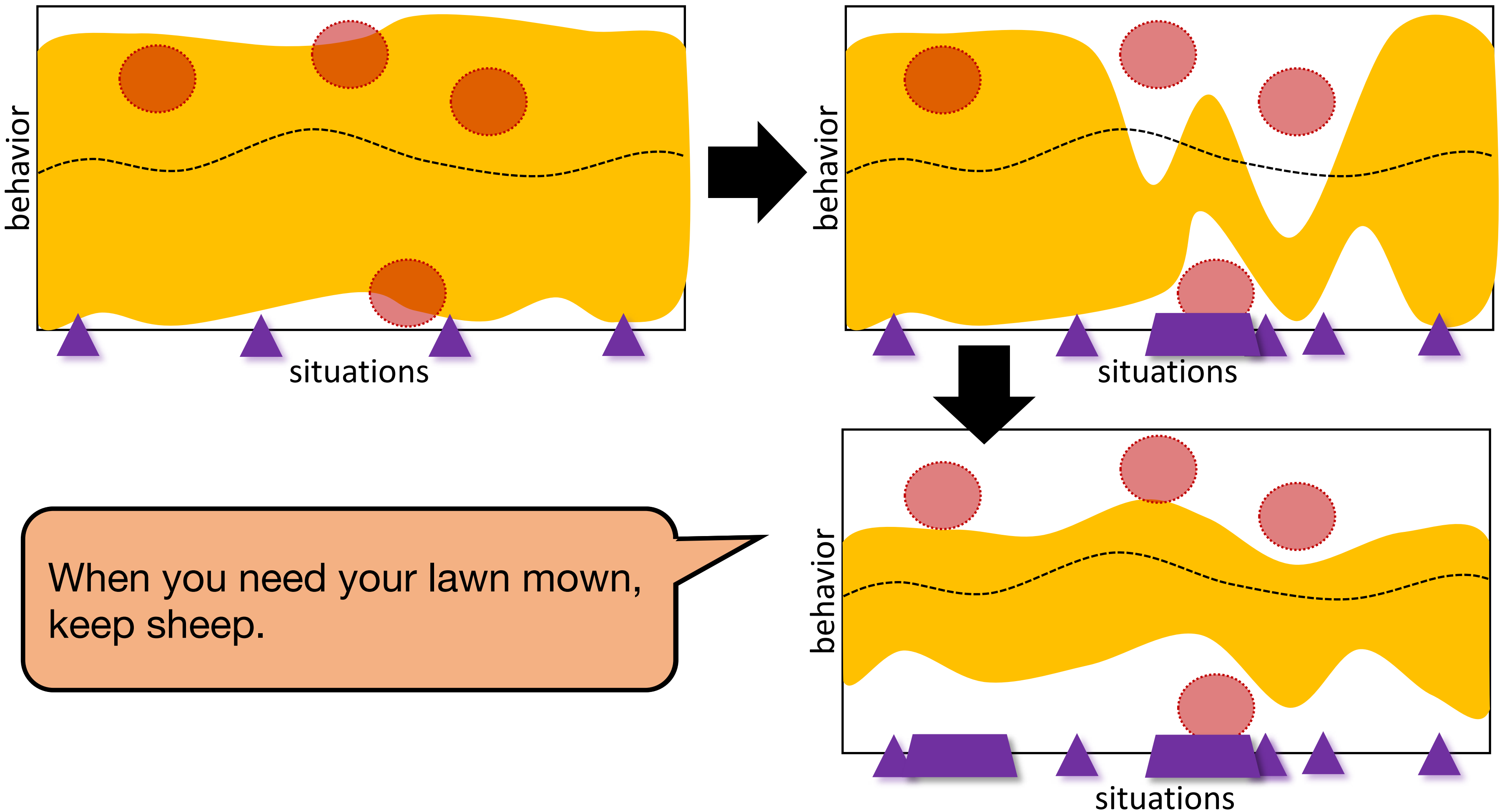
Coevolution



Coevolution

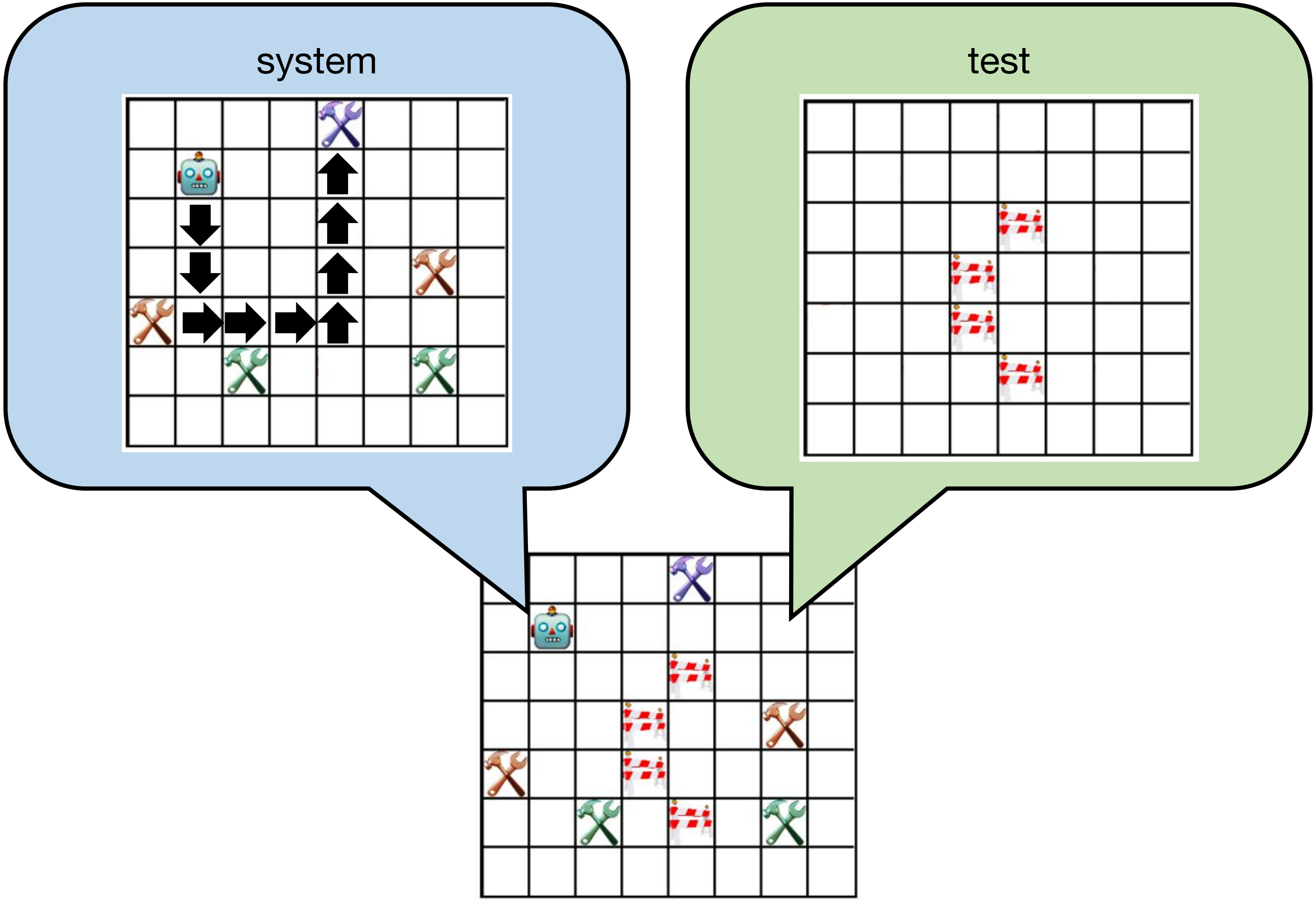


Coevolution

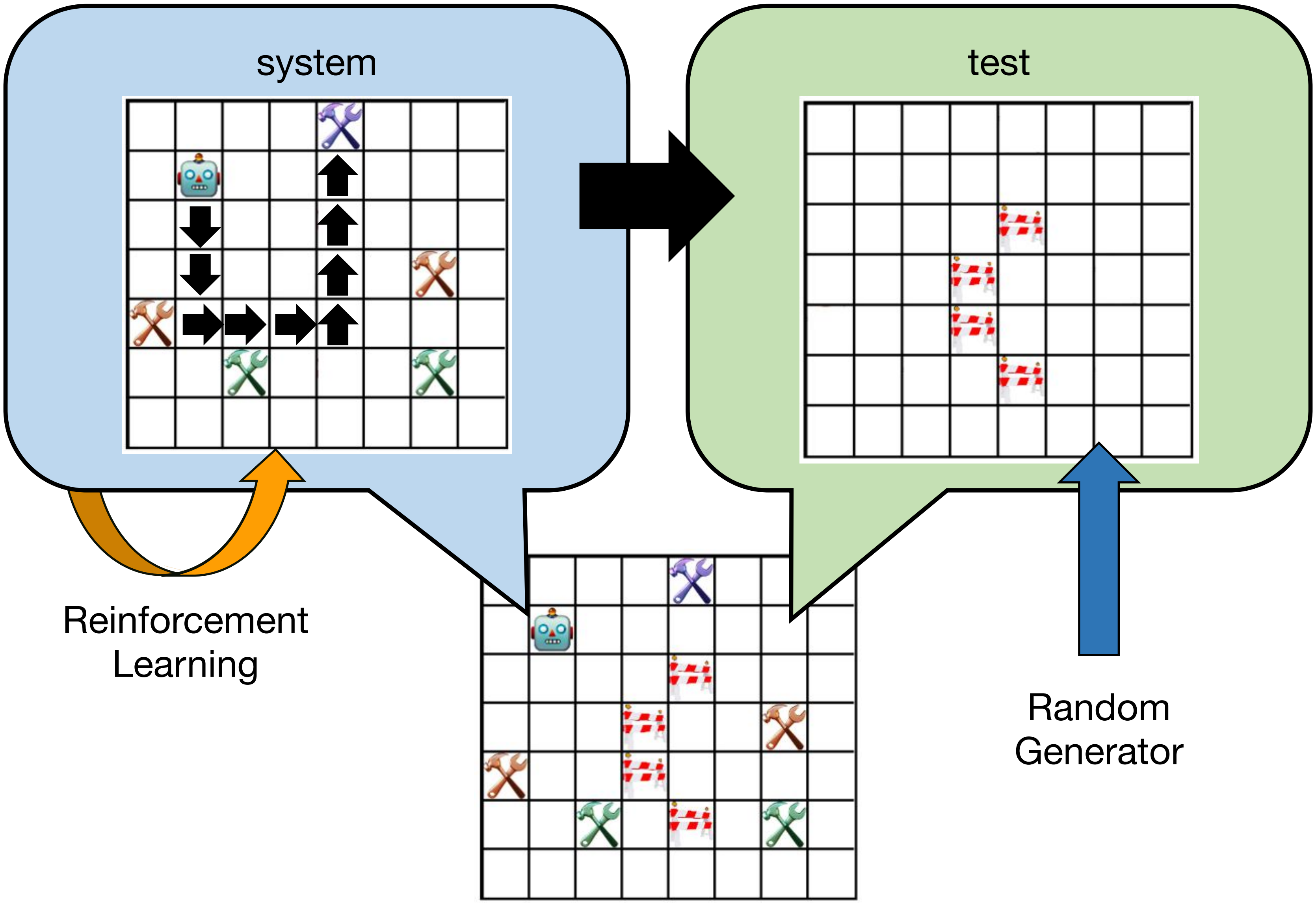


Scenario Co-Evolution with Reinforcement Learning and Evolutionary Algorithms

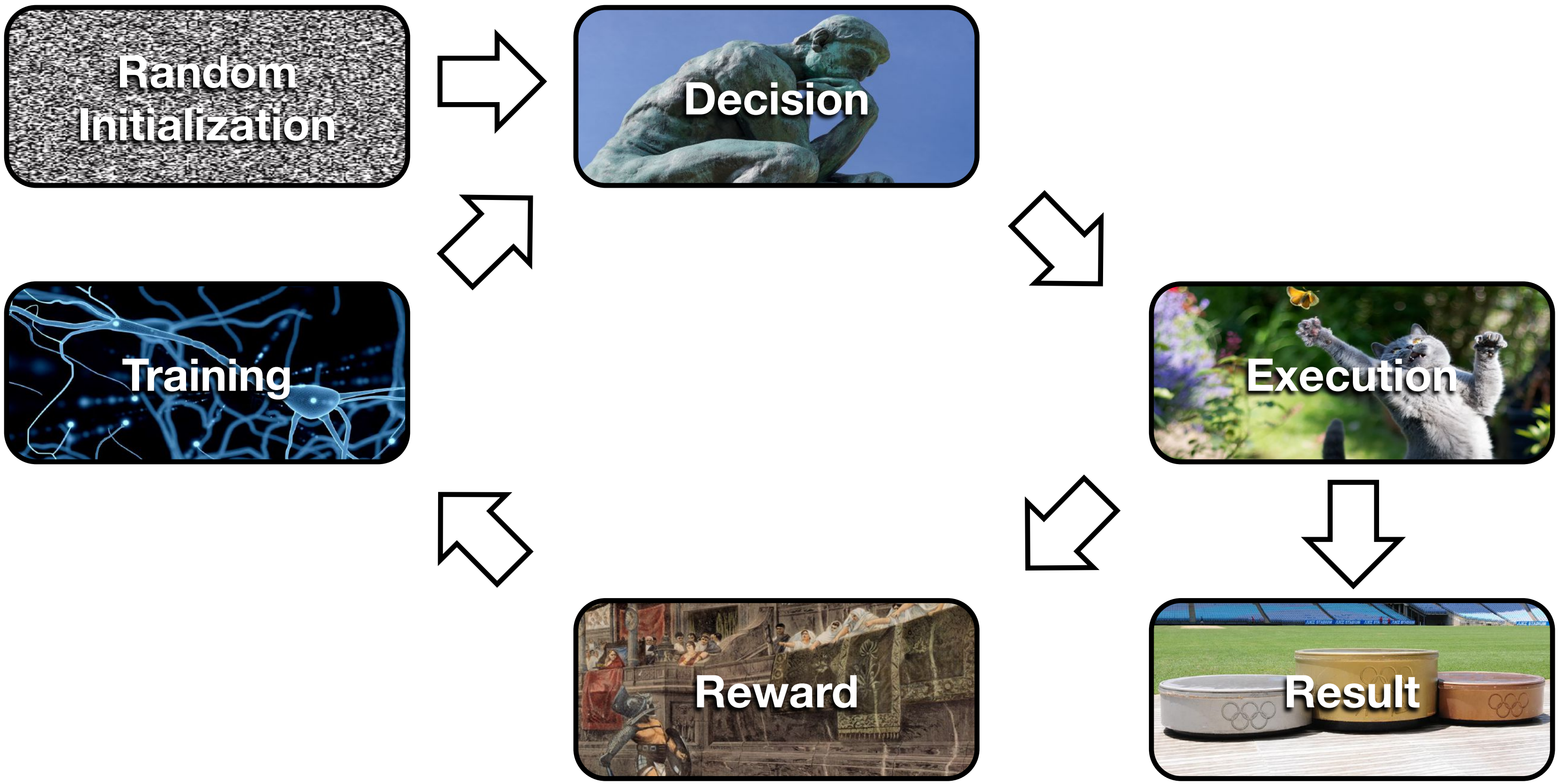
The Small Picture



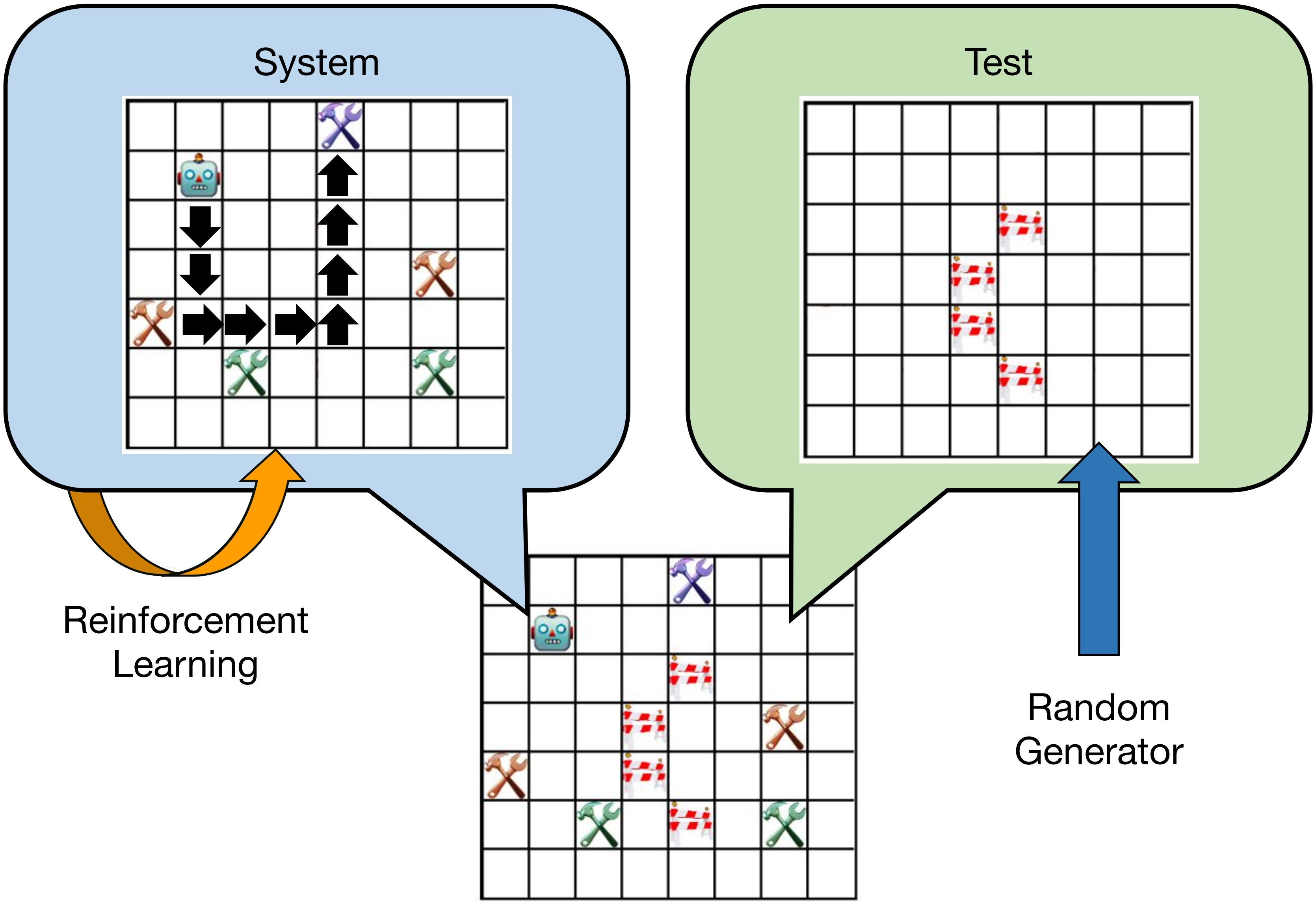
The Small Picture



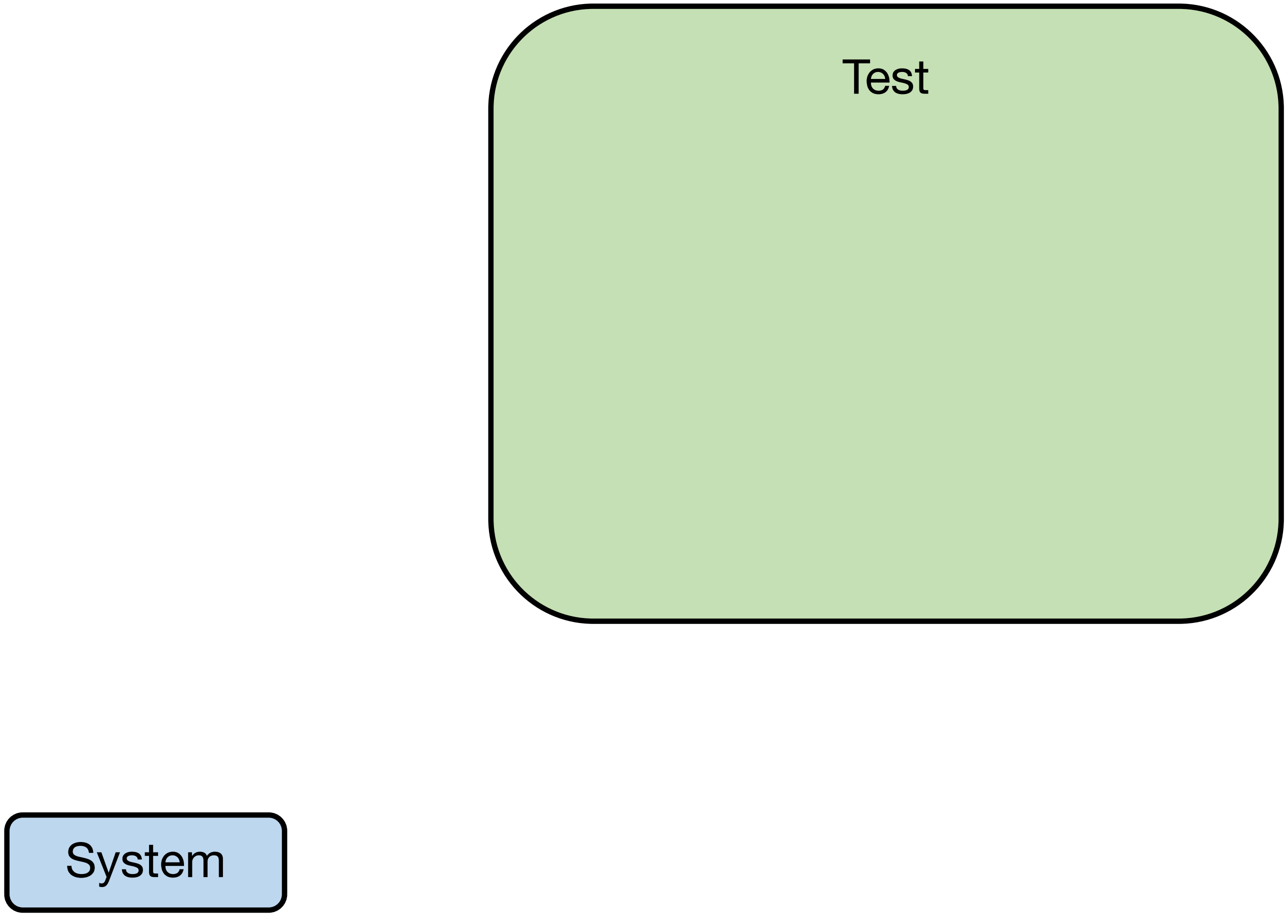
Reinforcement Learning



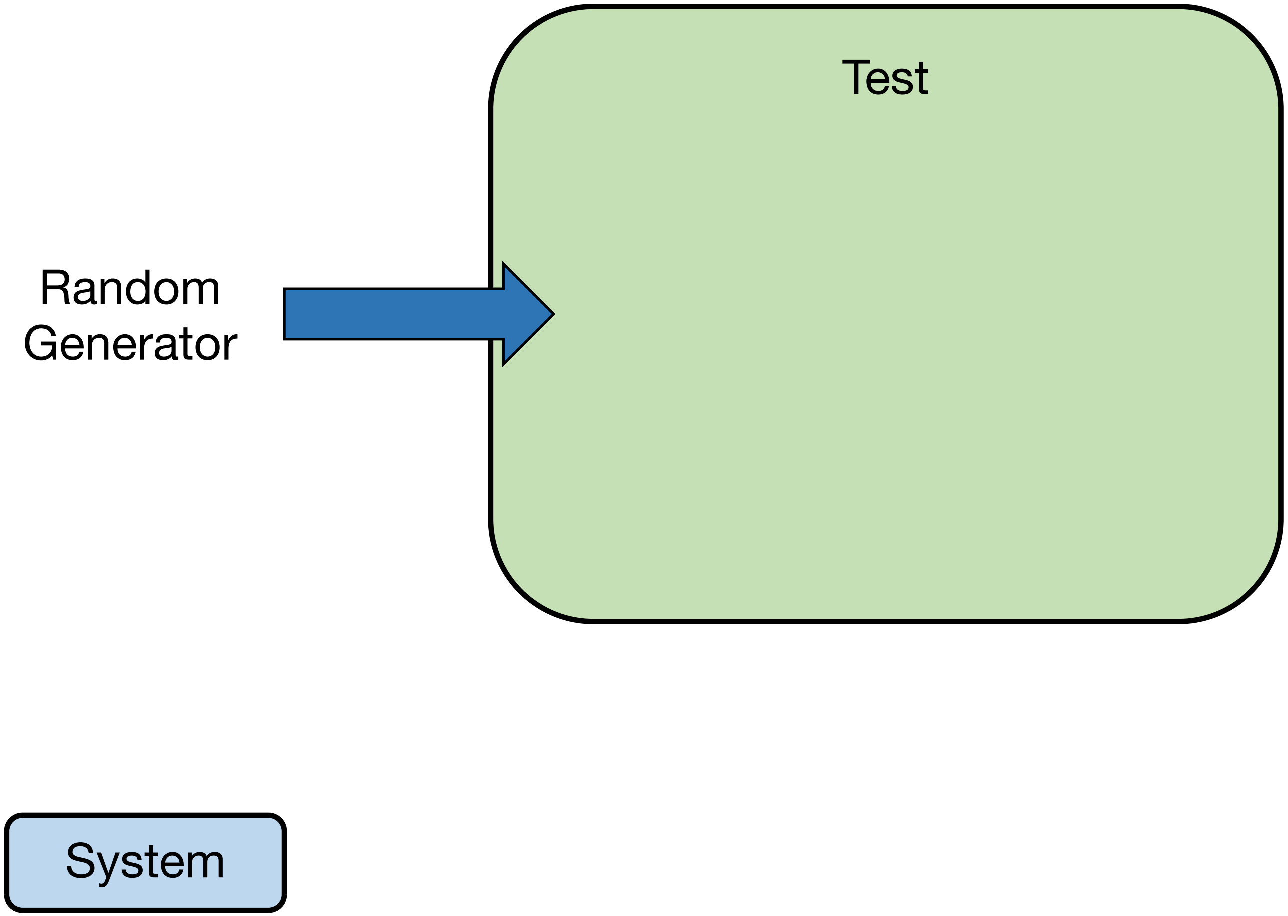
Training against Random Test



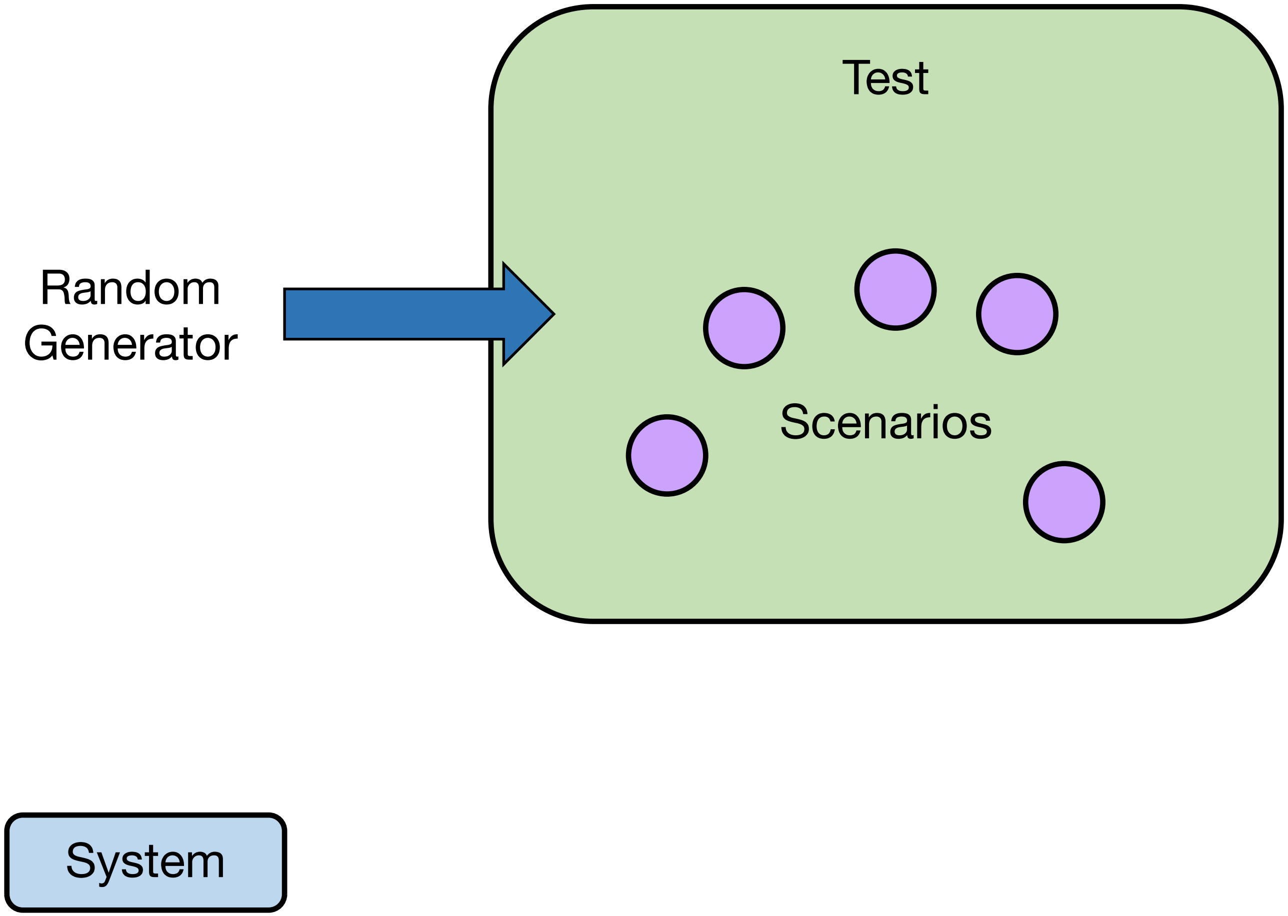
Training against Random Test



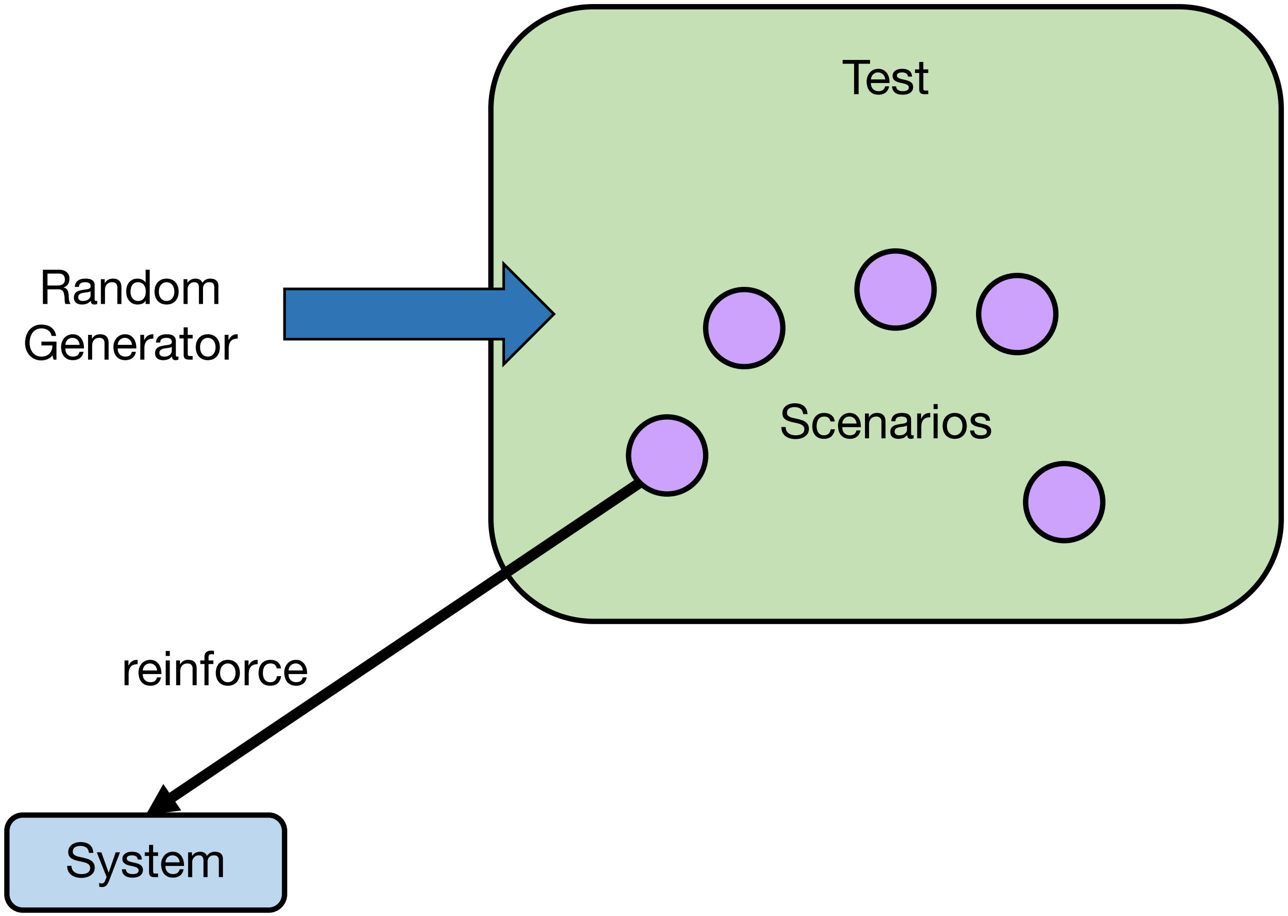
Training against Random Test



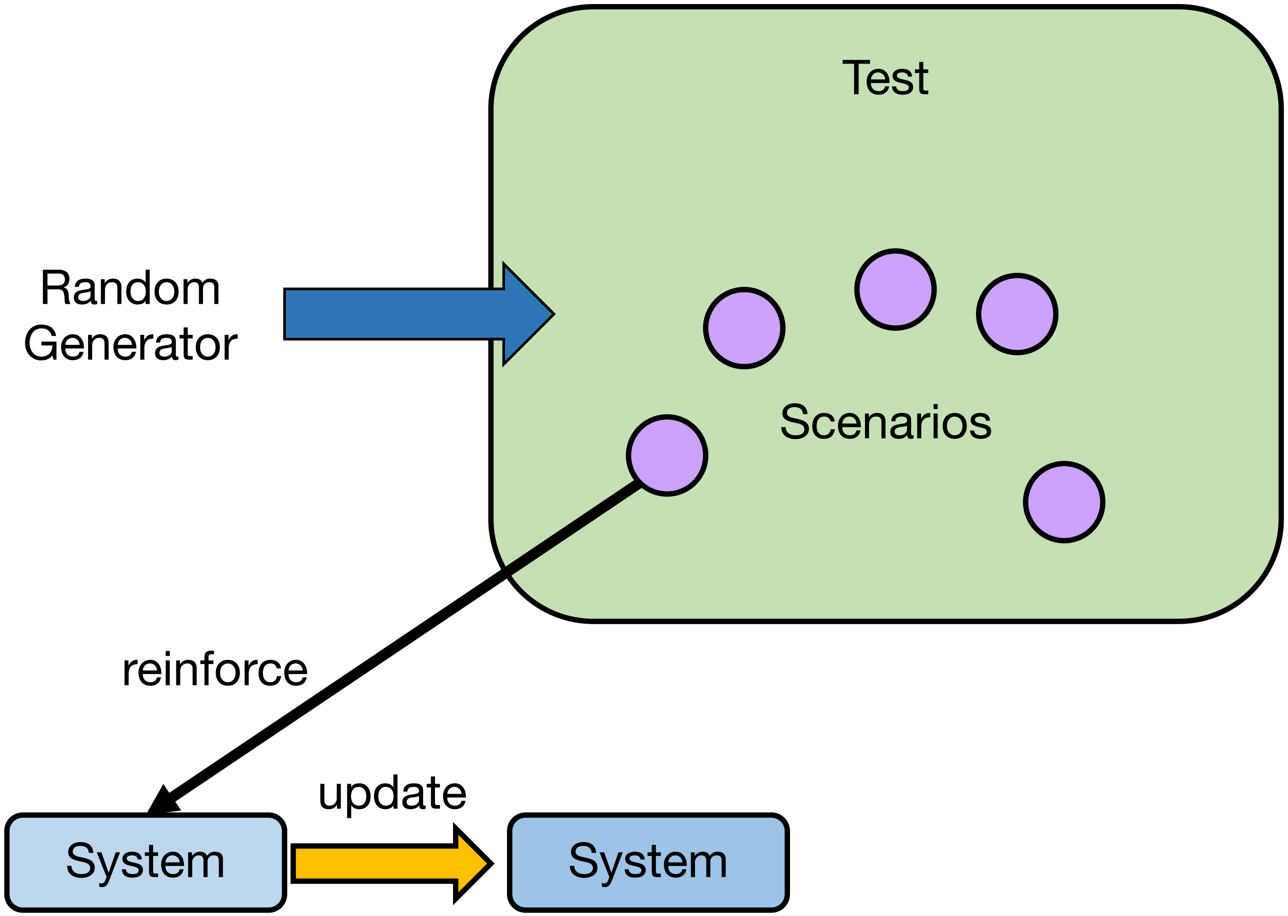
Training against Random Test



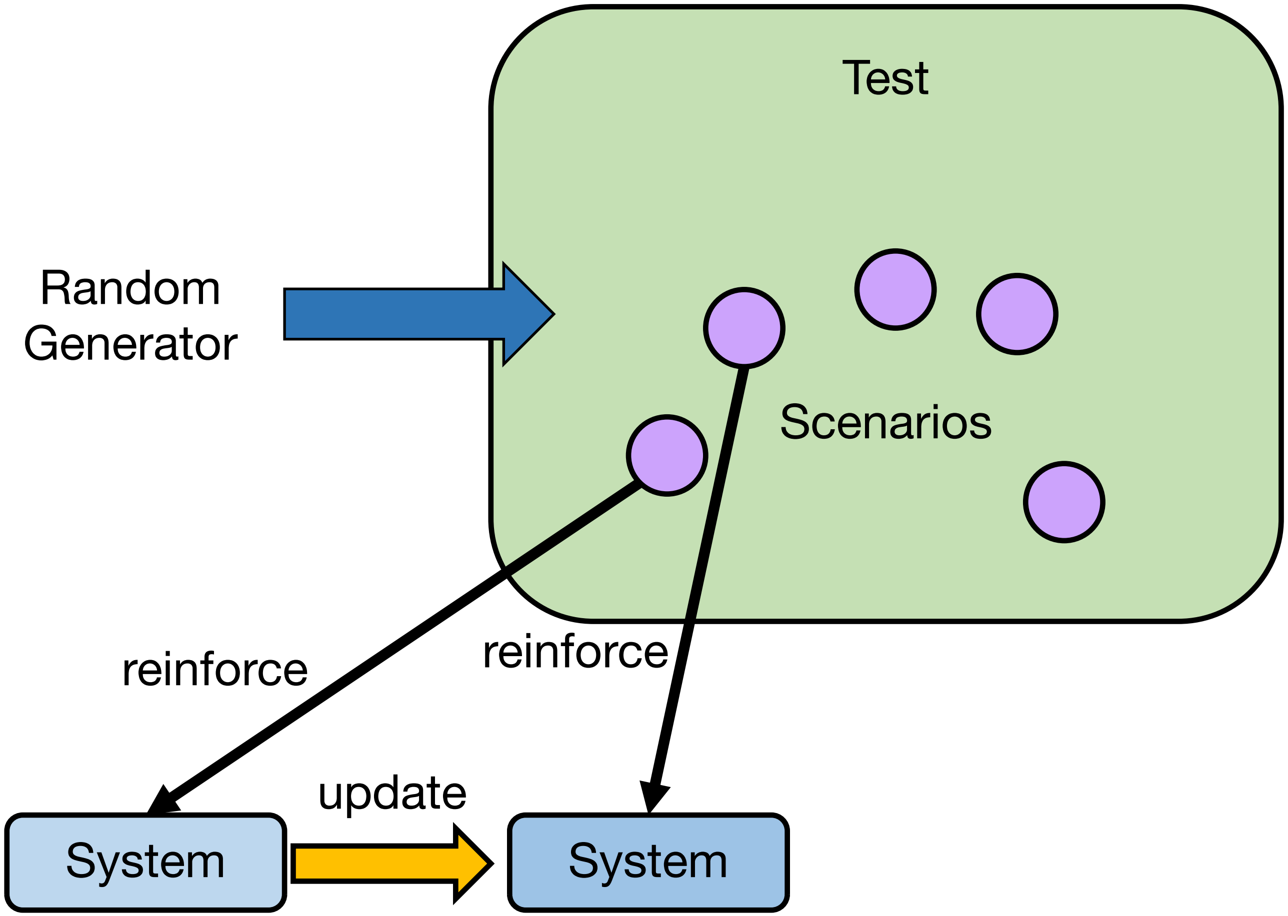
Training against Random Test



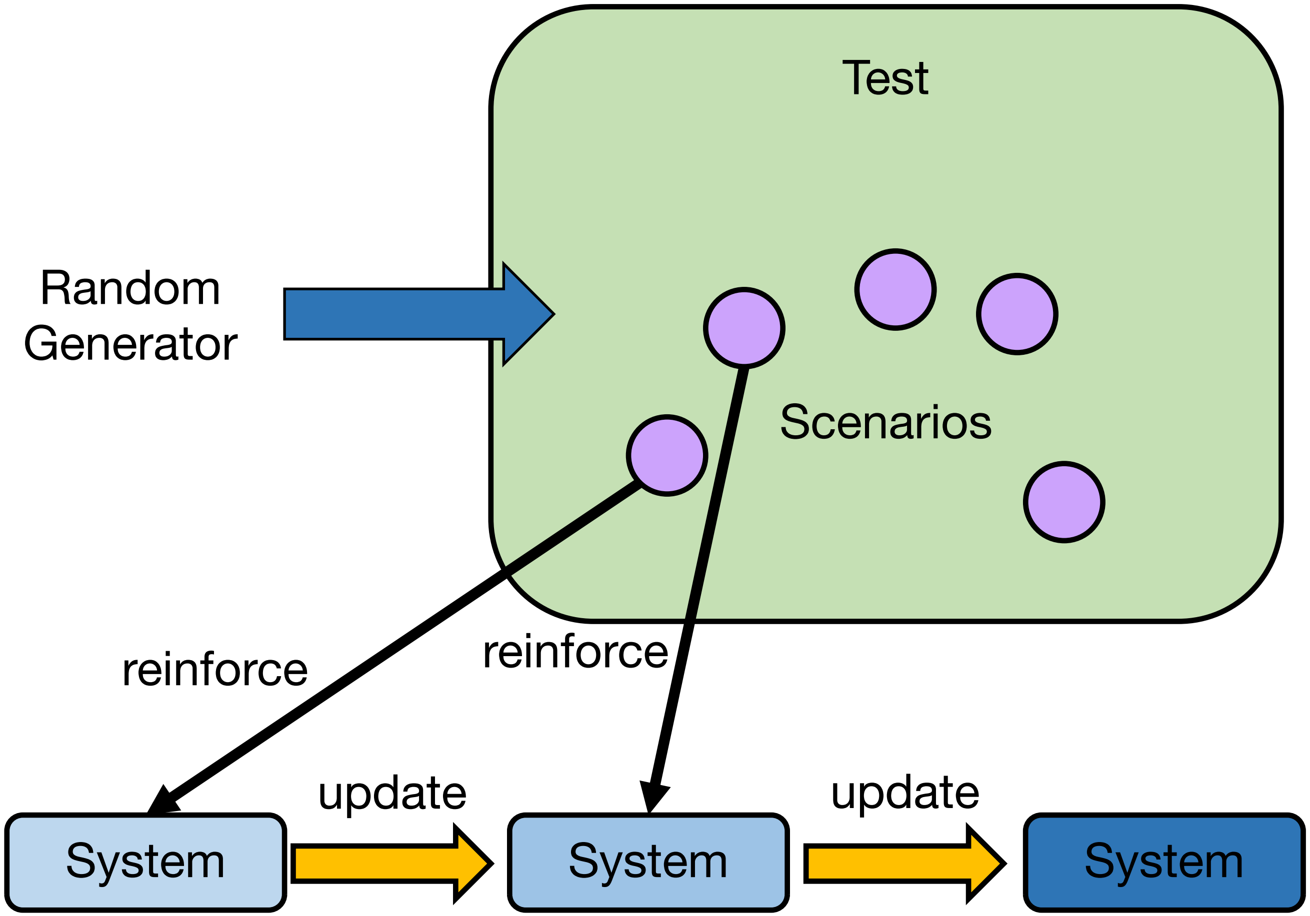
Training against Random Test



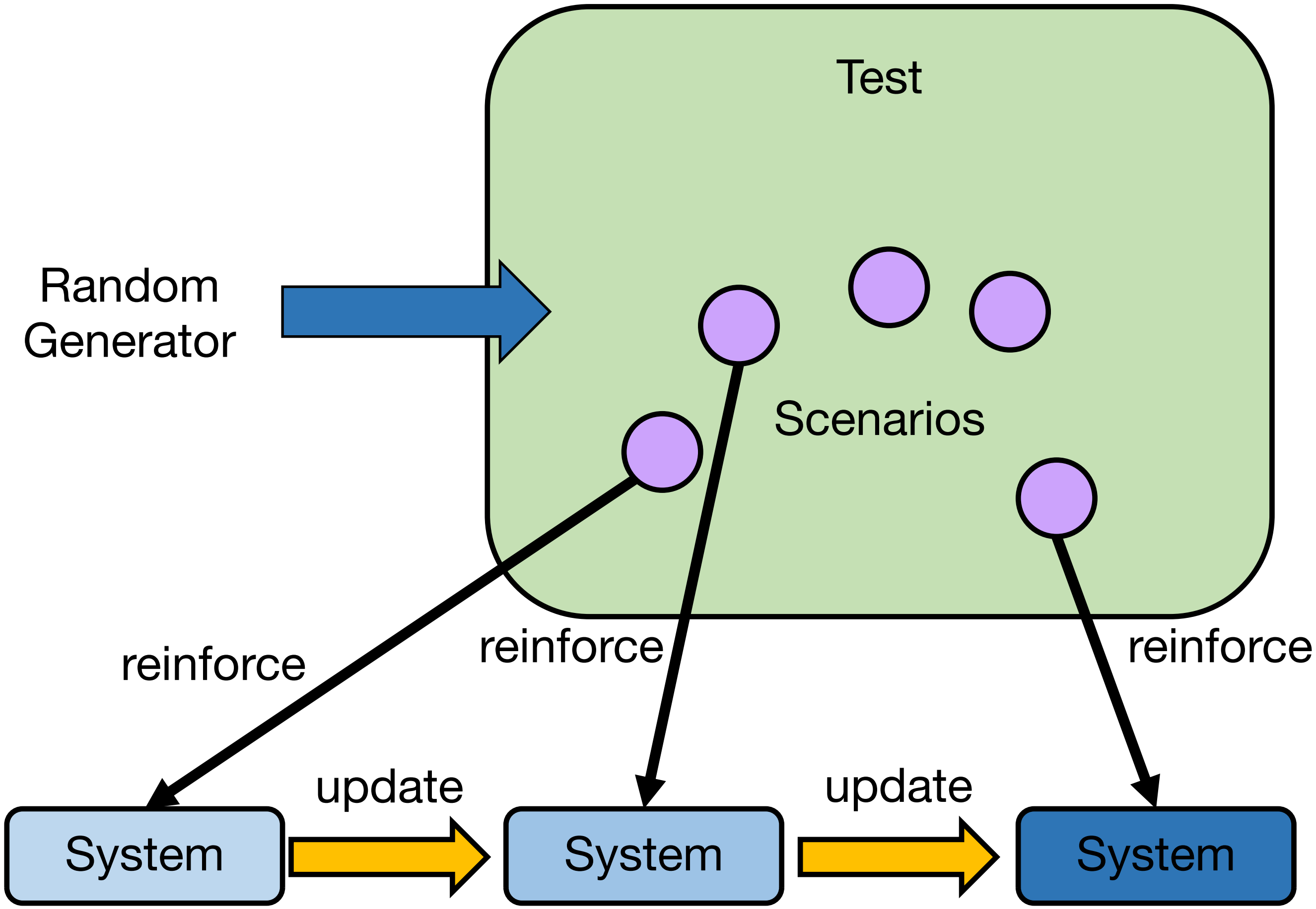
Training against Random Test



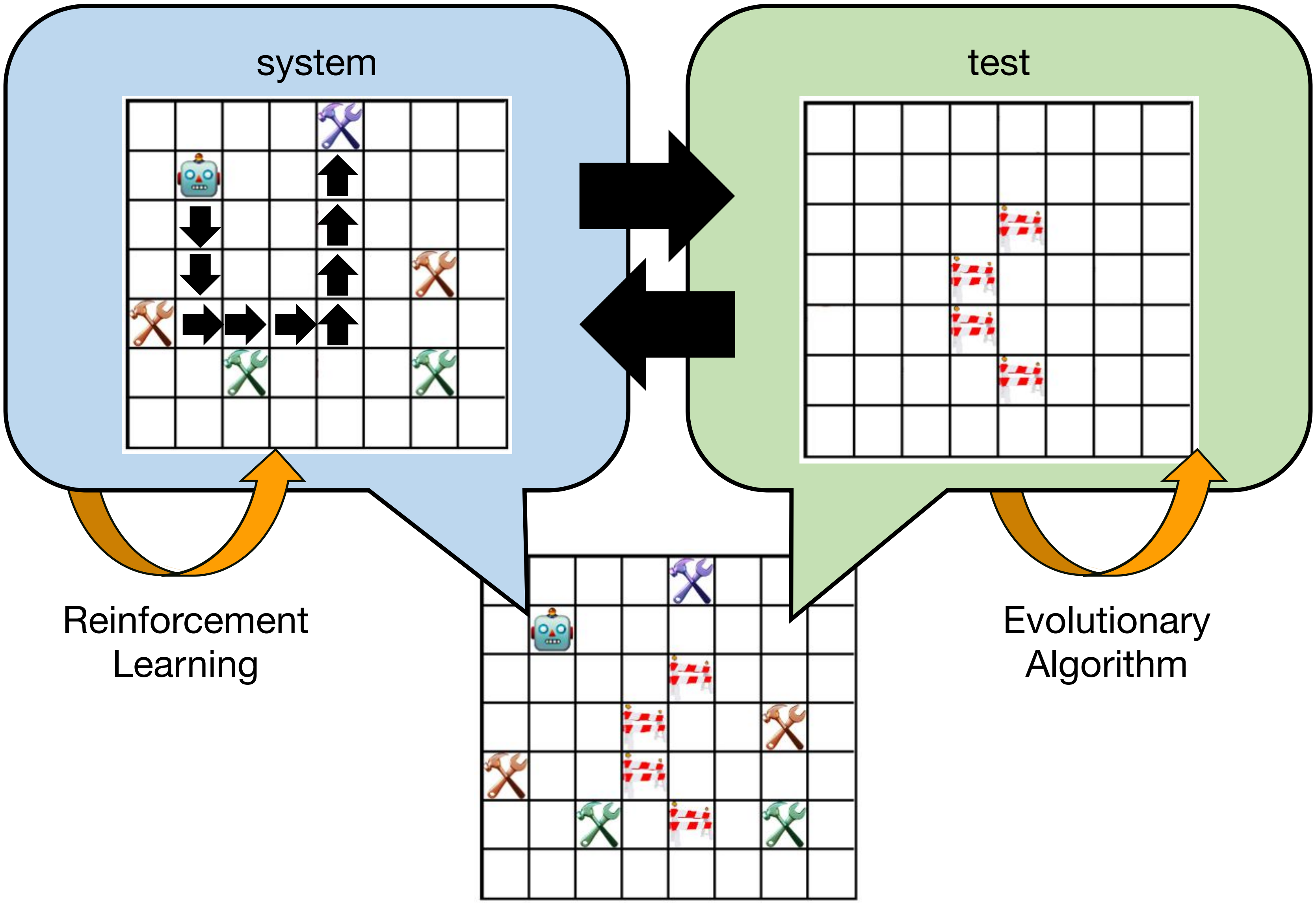
Training against Random Test



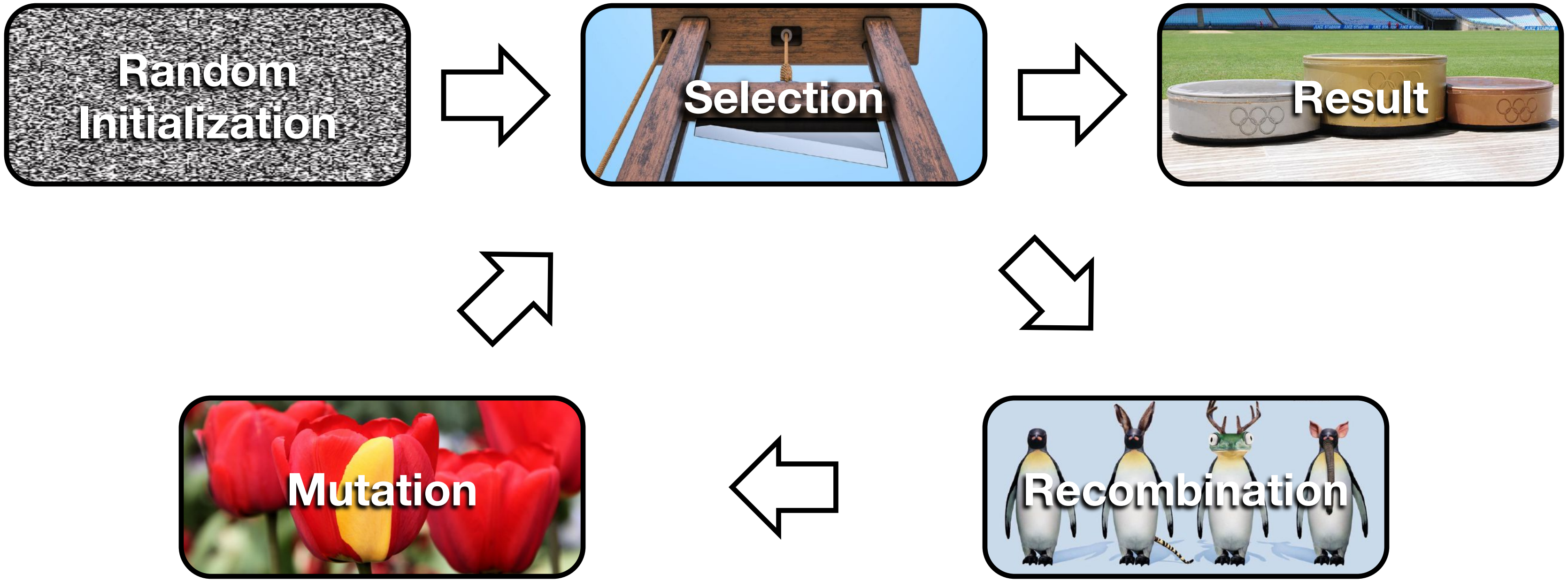
Training against Random Test



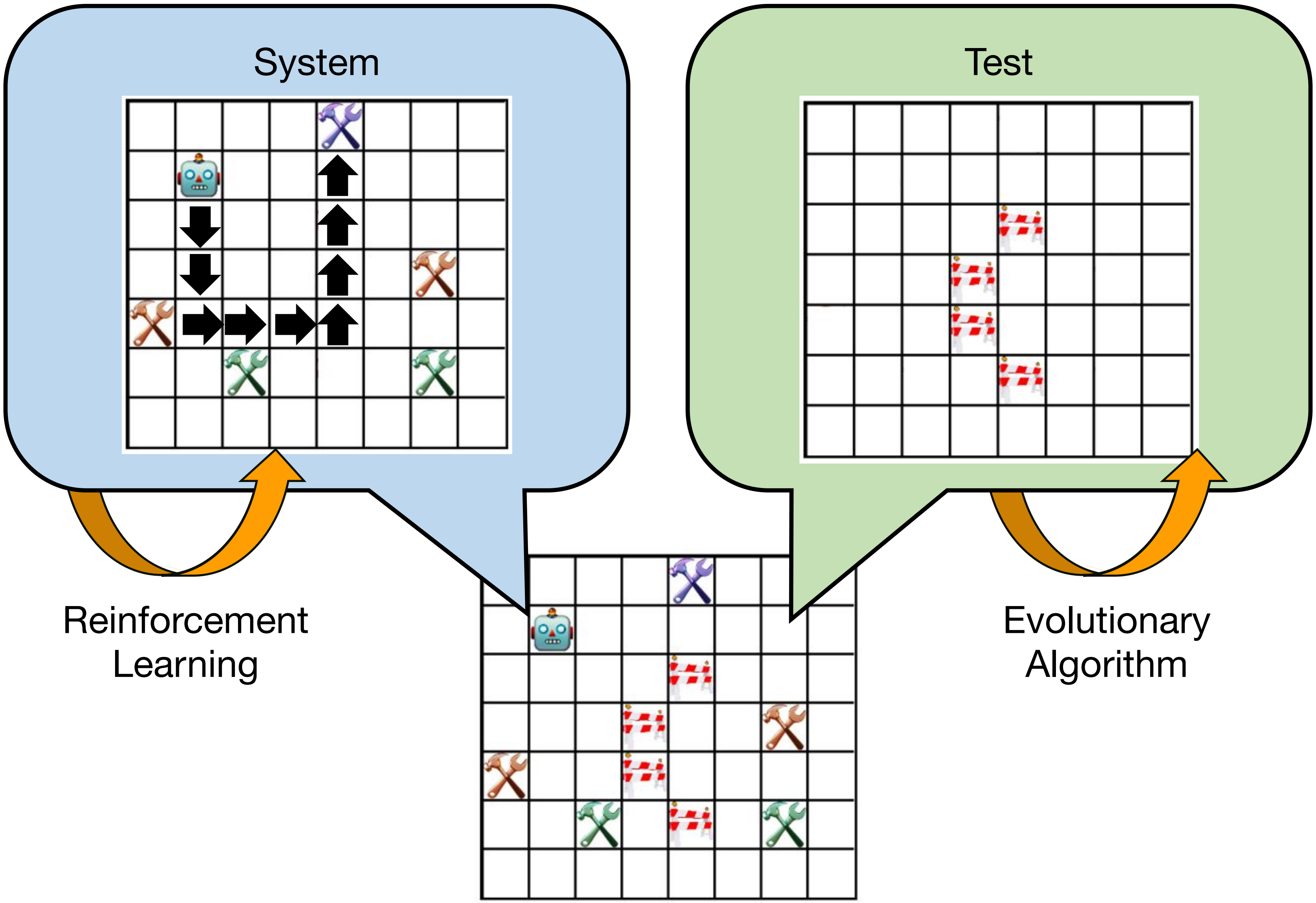
The Small Picture



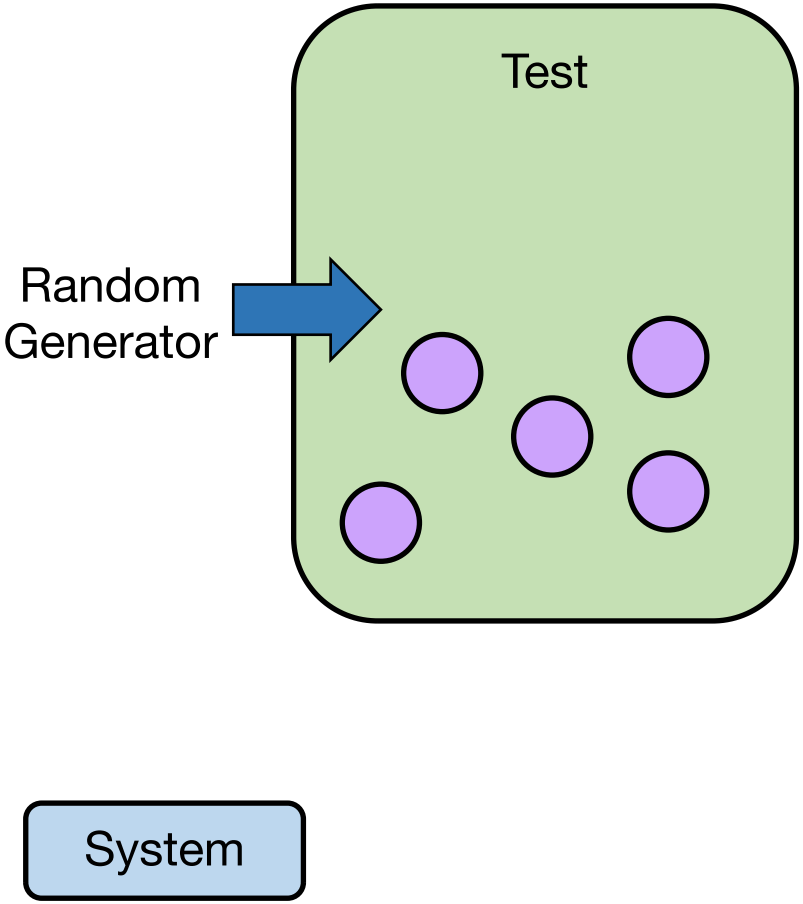
Evolutionary Algorithms



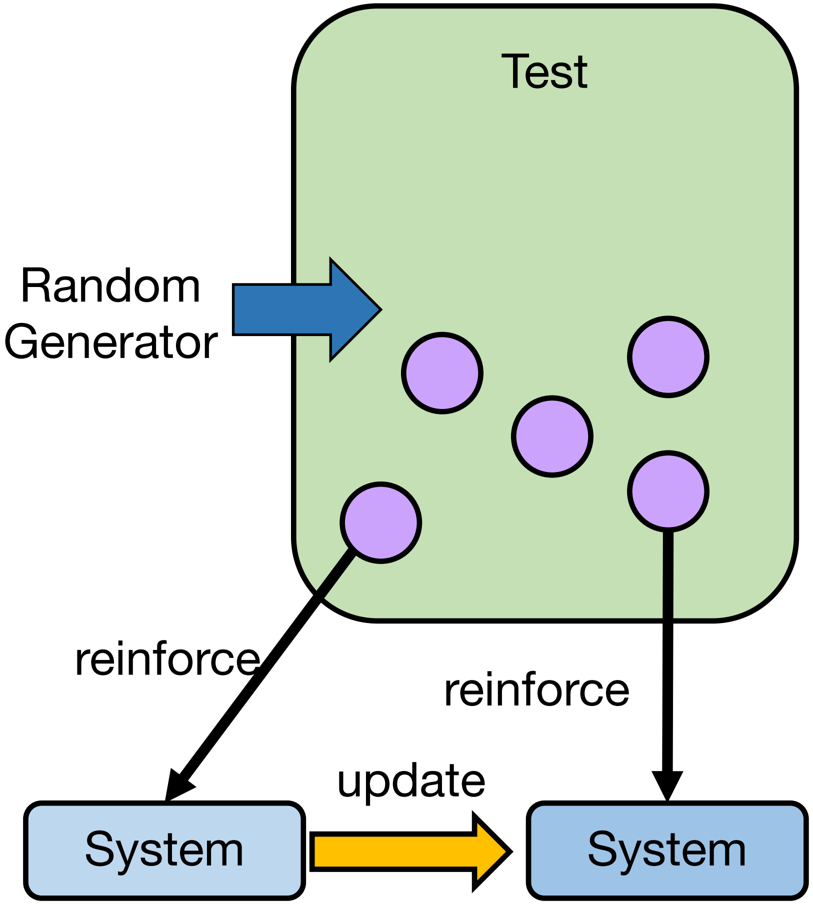
Training against SCoE Test



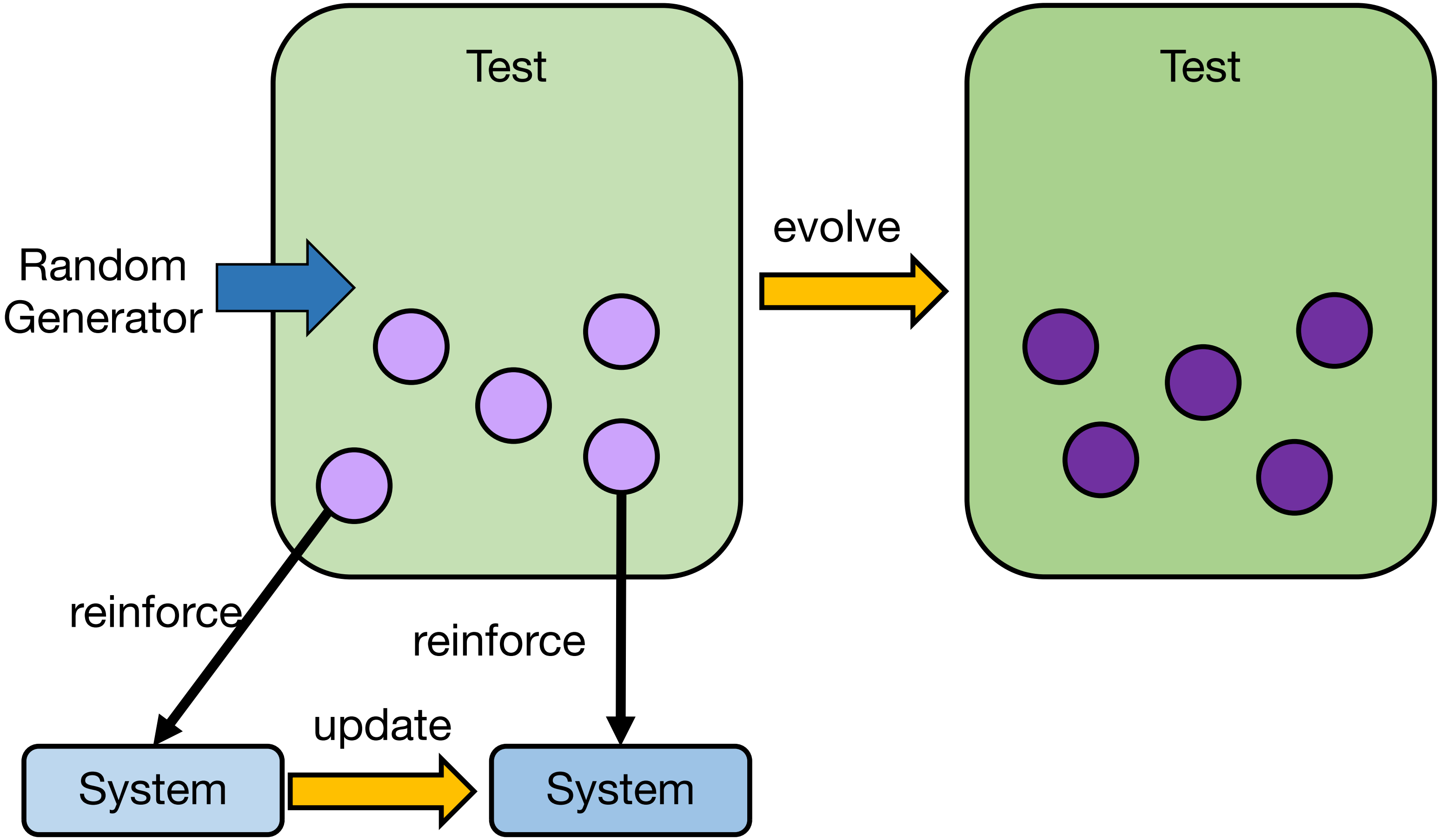
Training against SCoE Test



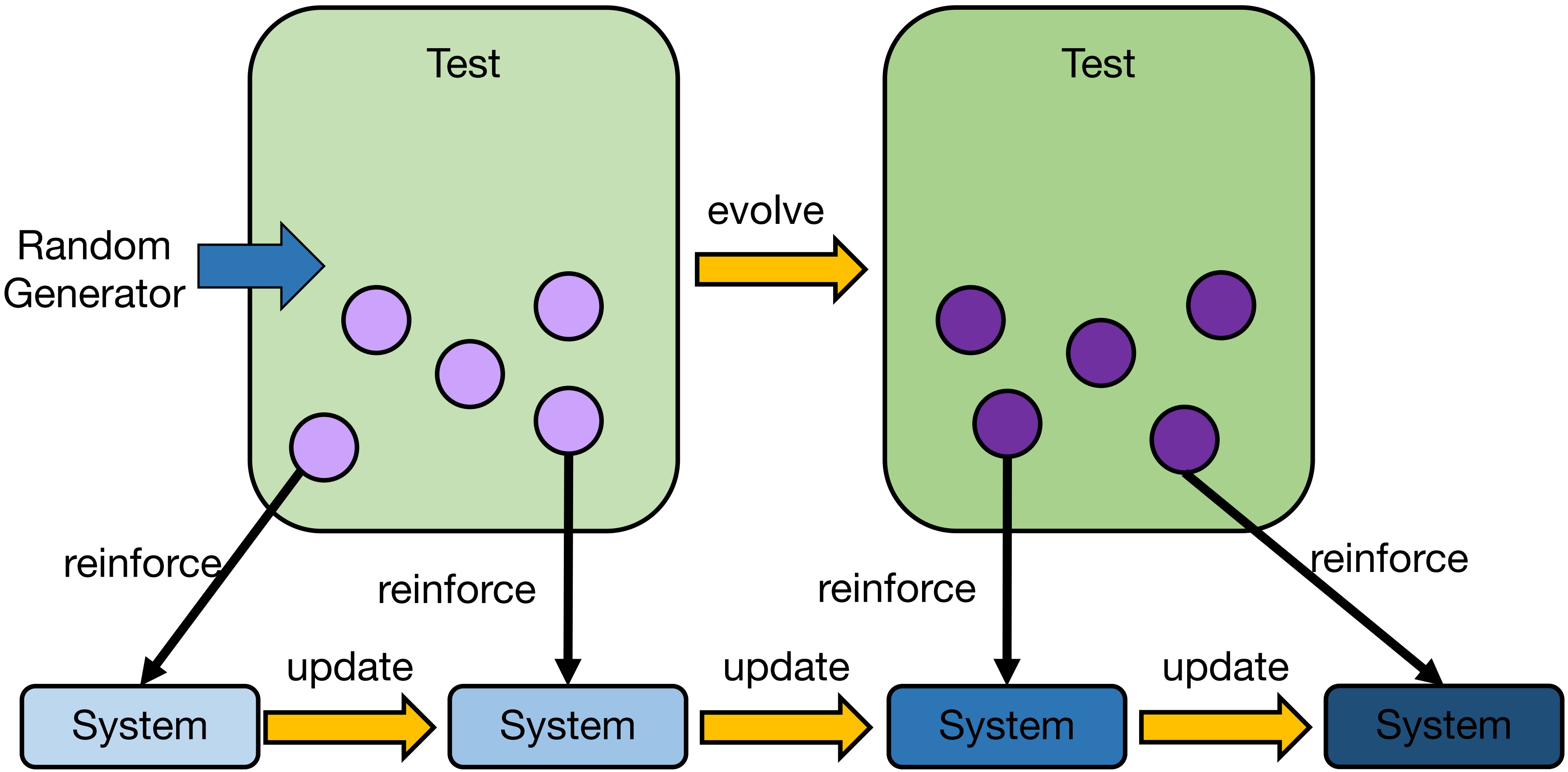
Training against SCoE Test



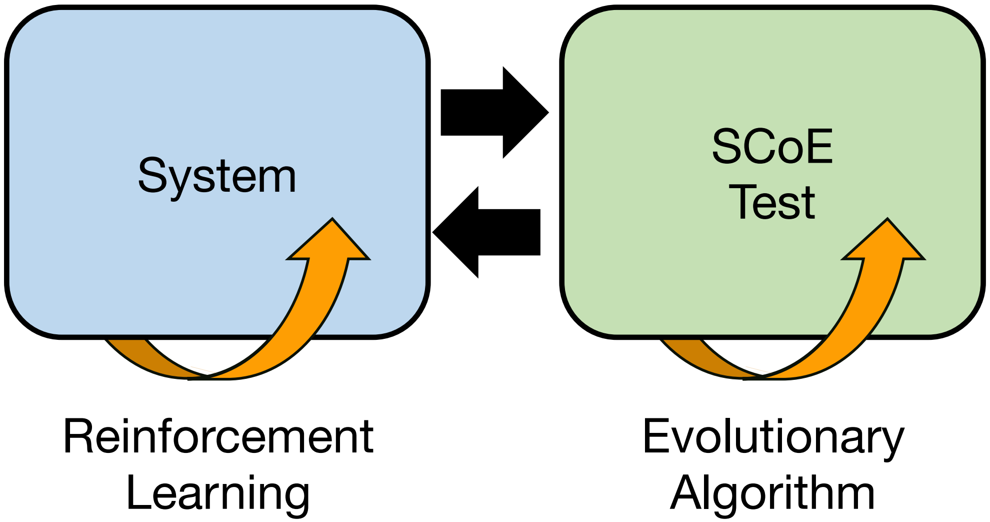
Training against SCoE Test

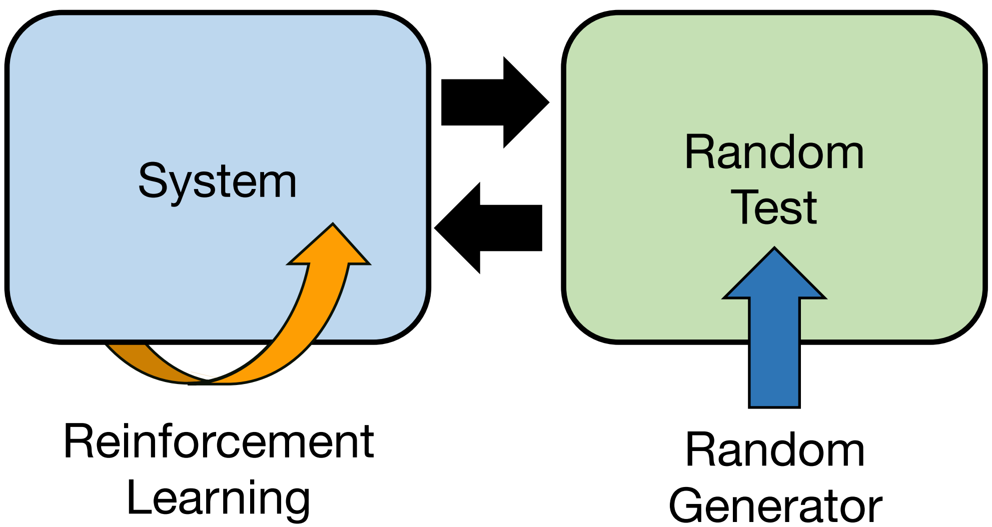


Training against SCoE Test

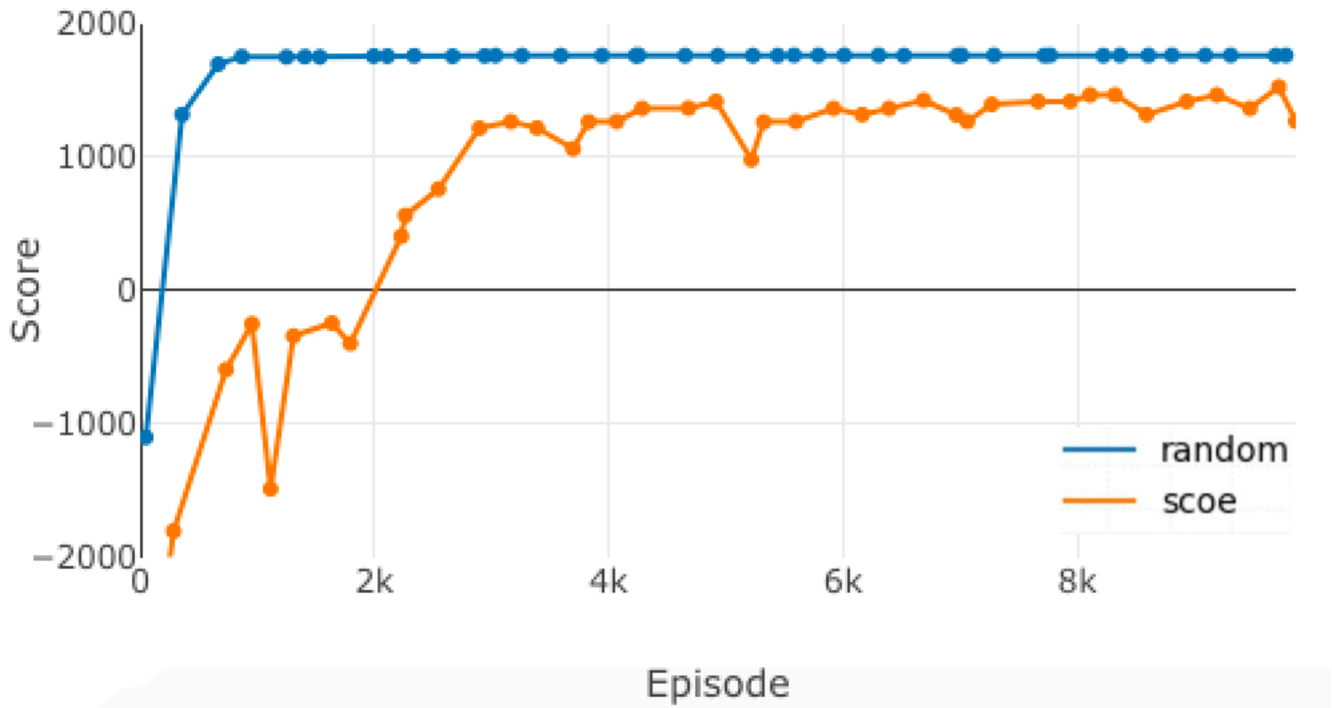


Experimental Setup

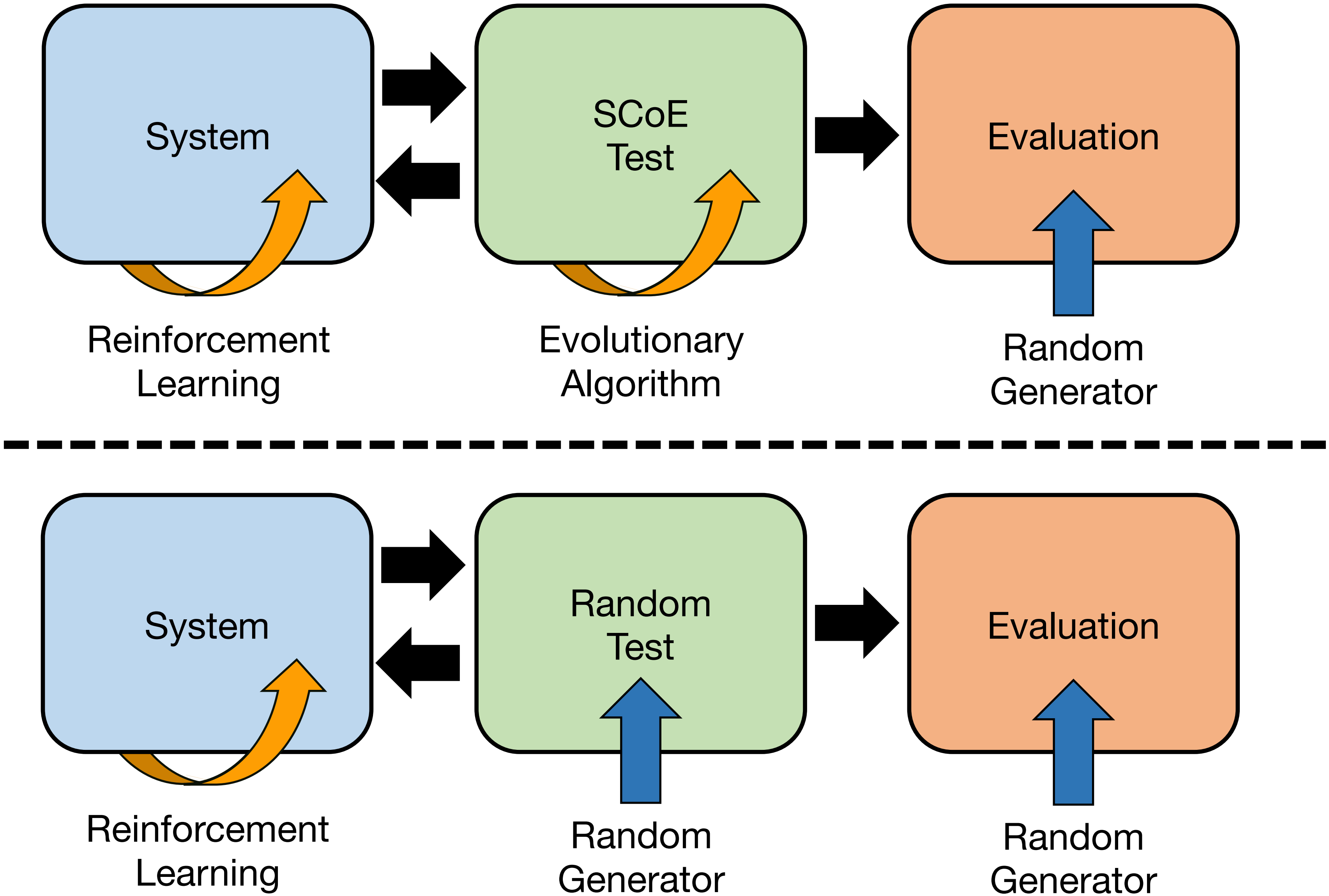




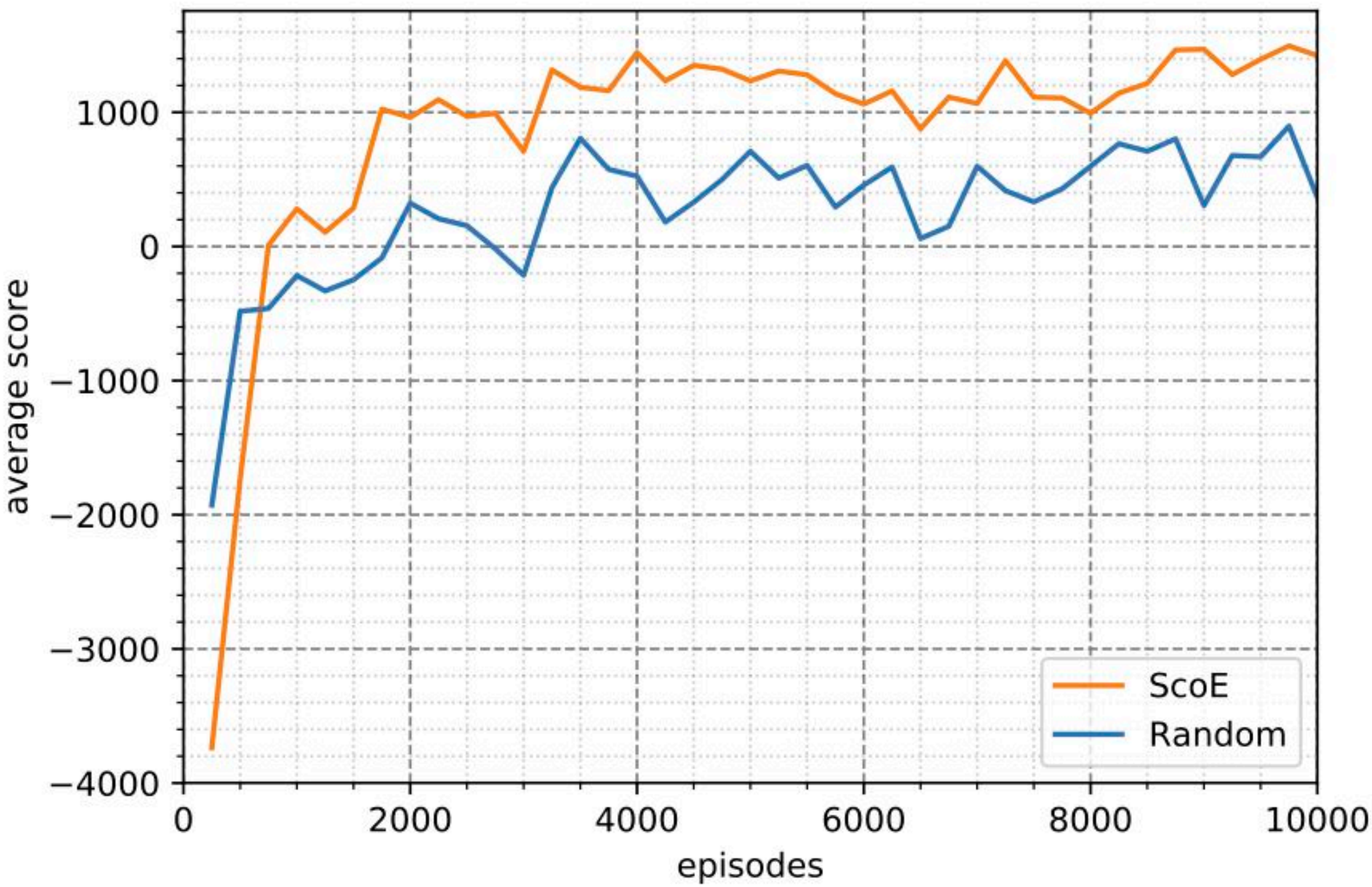
Learning Rates



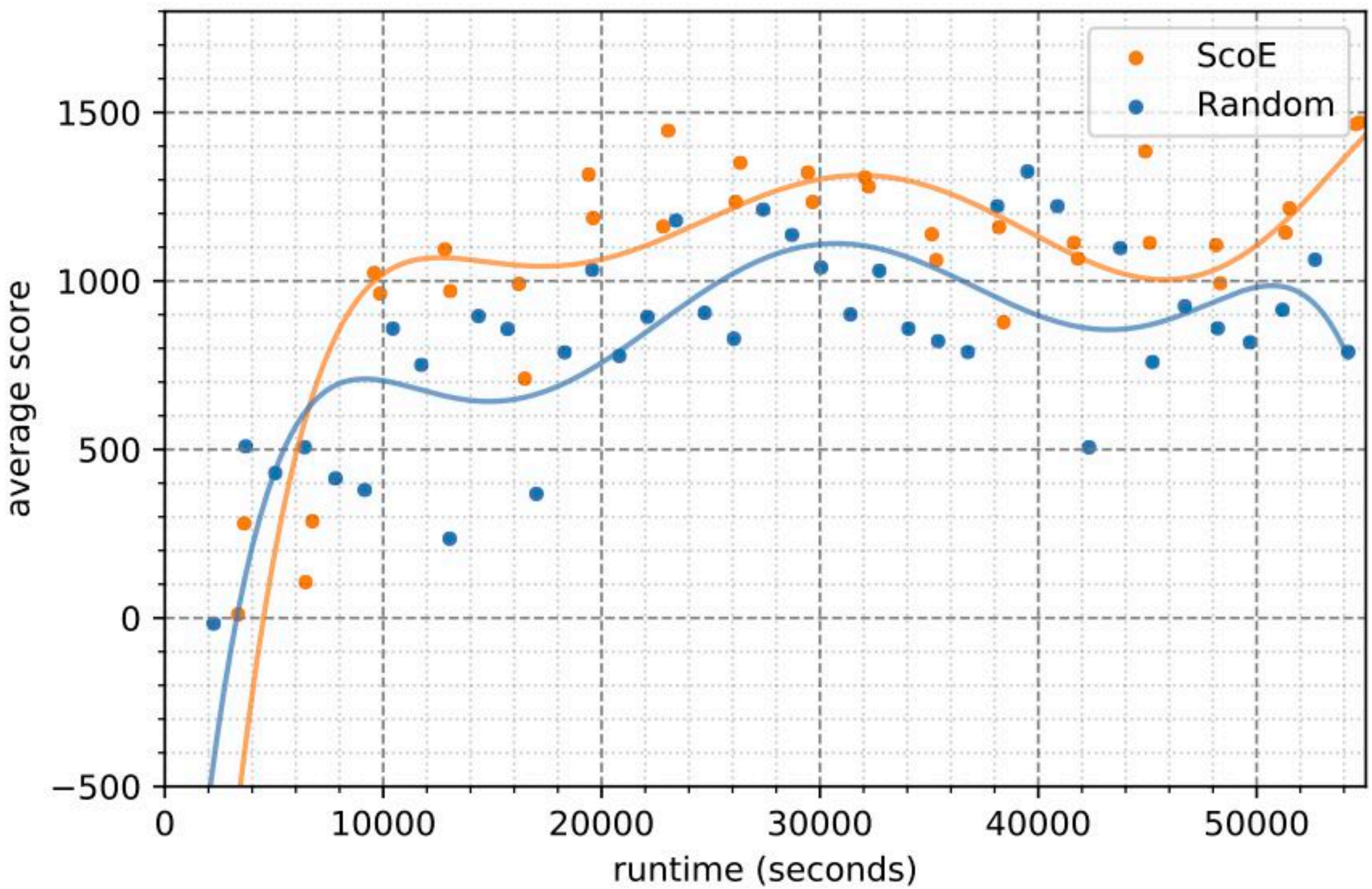
Experimental Setup



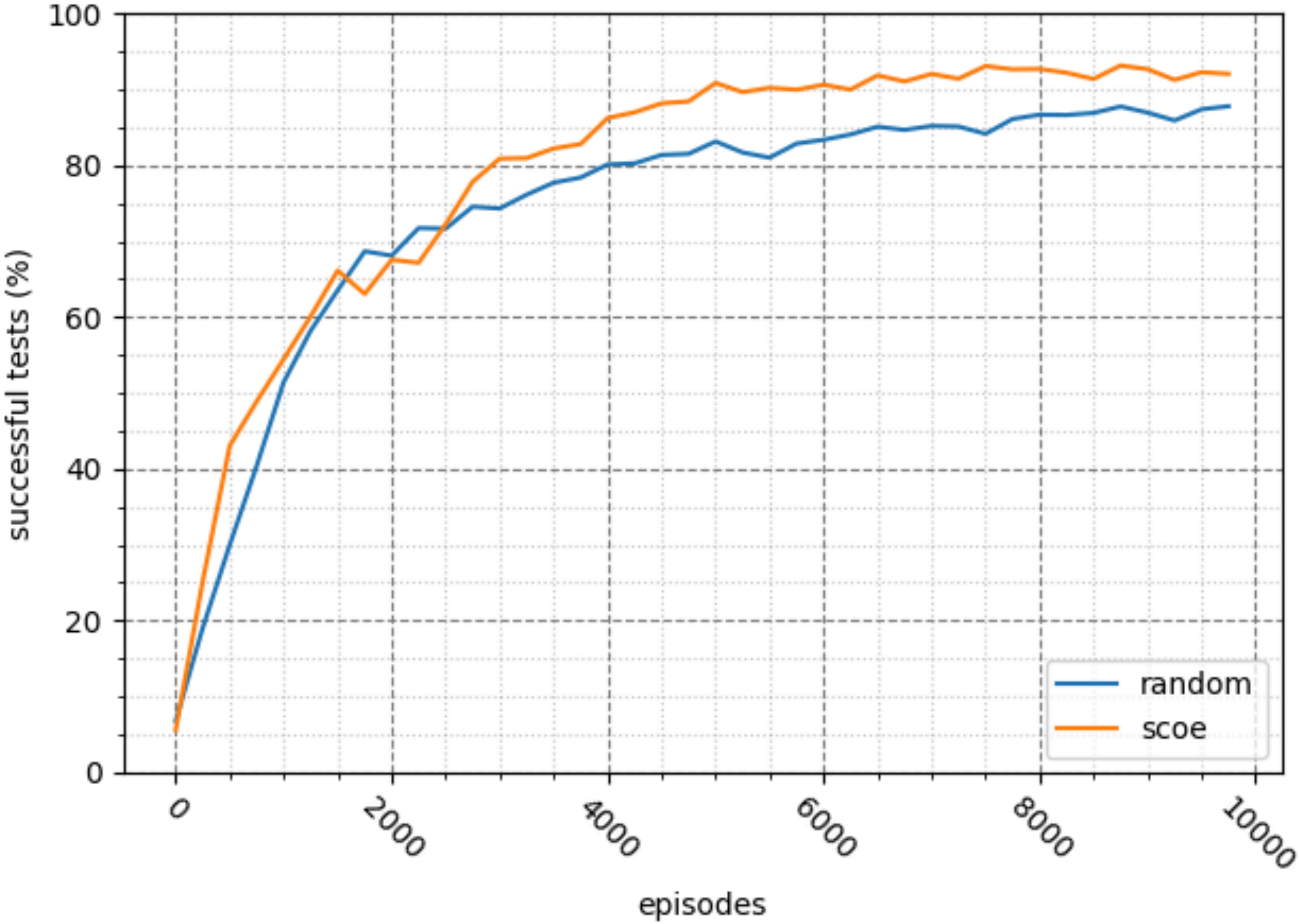
Effective Performance



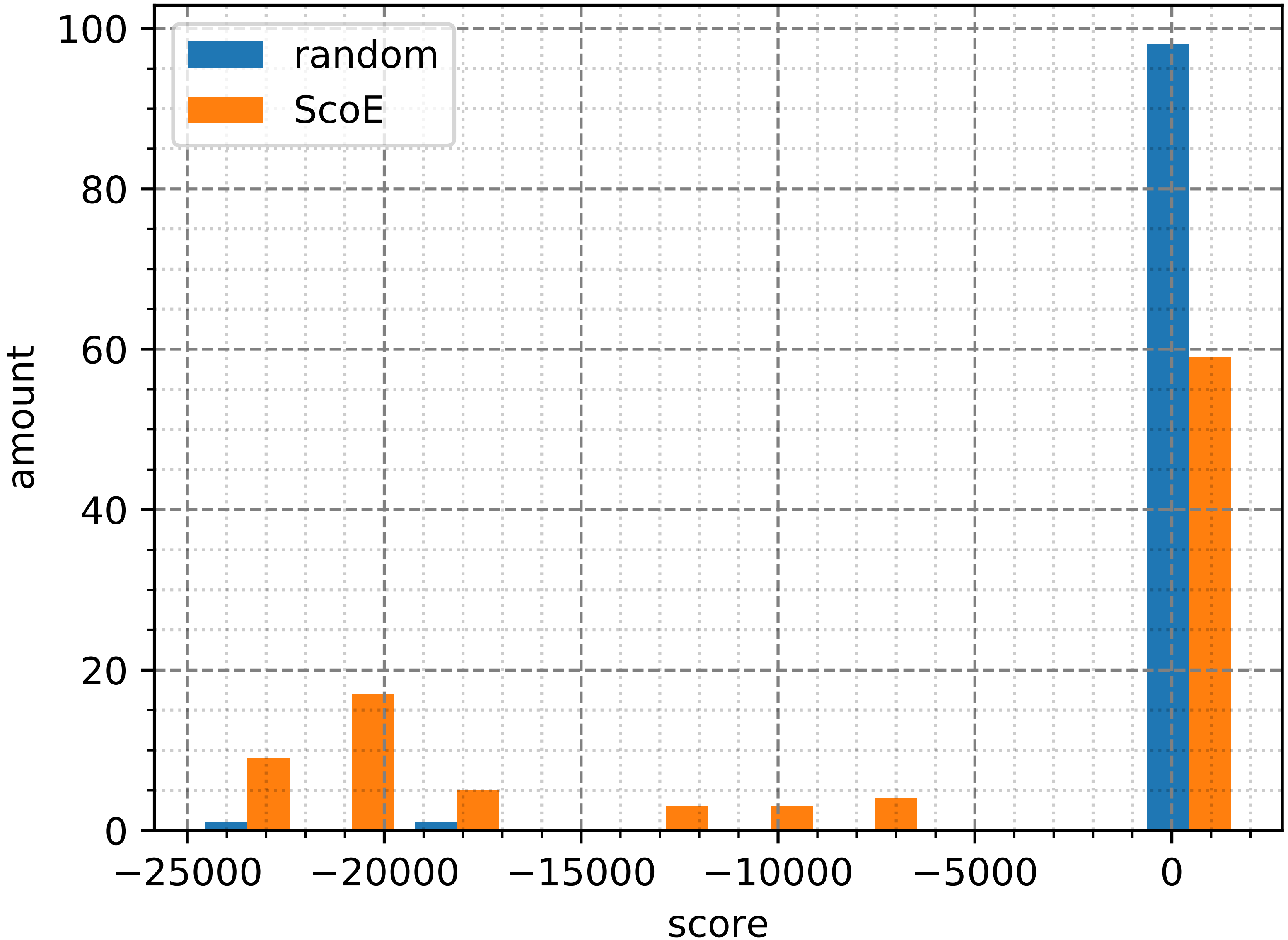
Performance over Time



Successful Runs

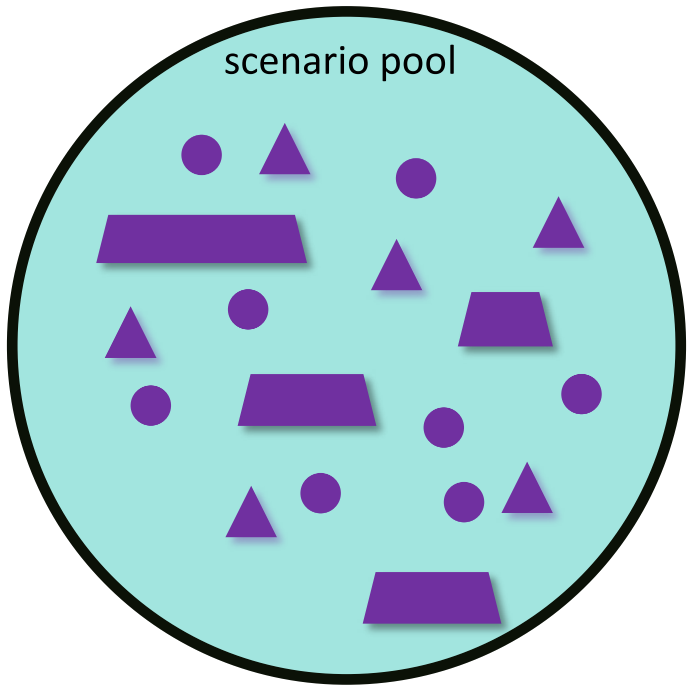


Generated Test Cases



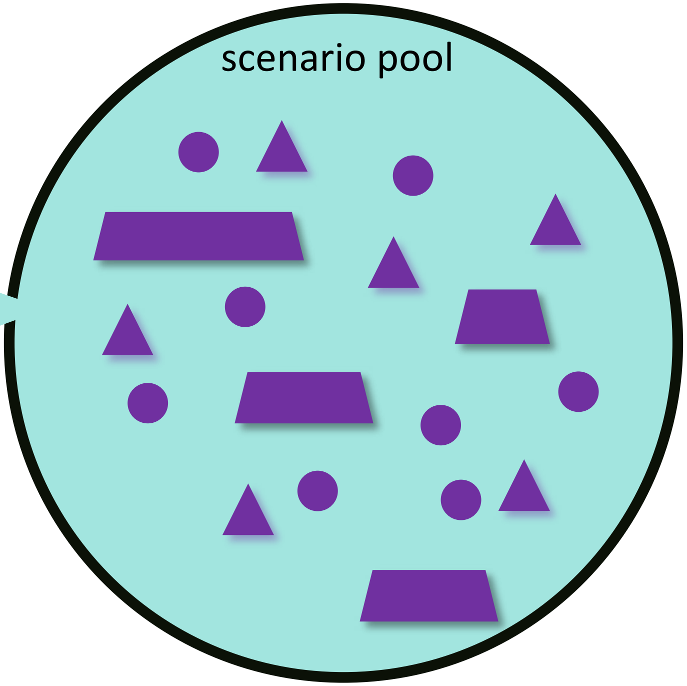
Scenario Co-Evolution as a Tool for Software Engineering

Criticality Focus

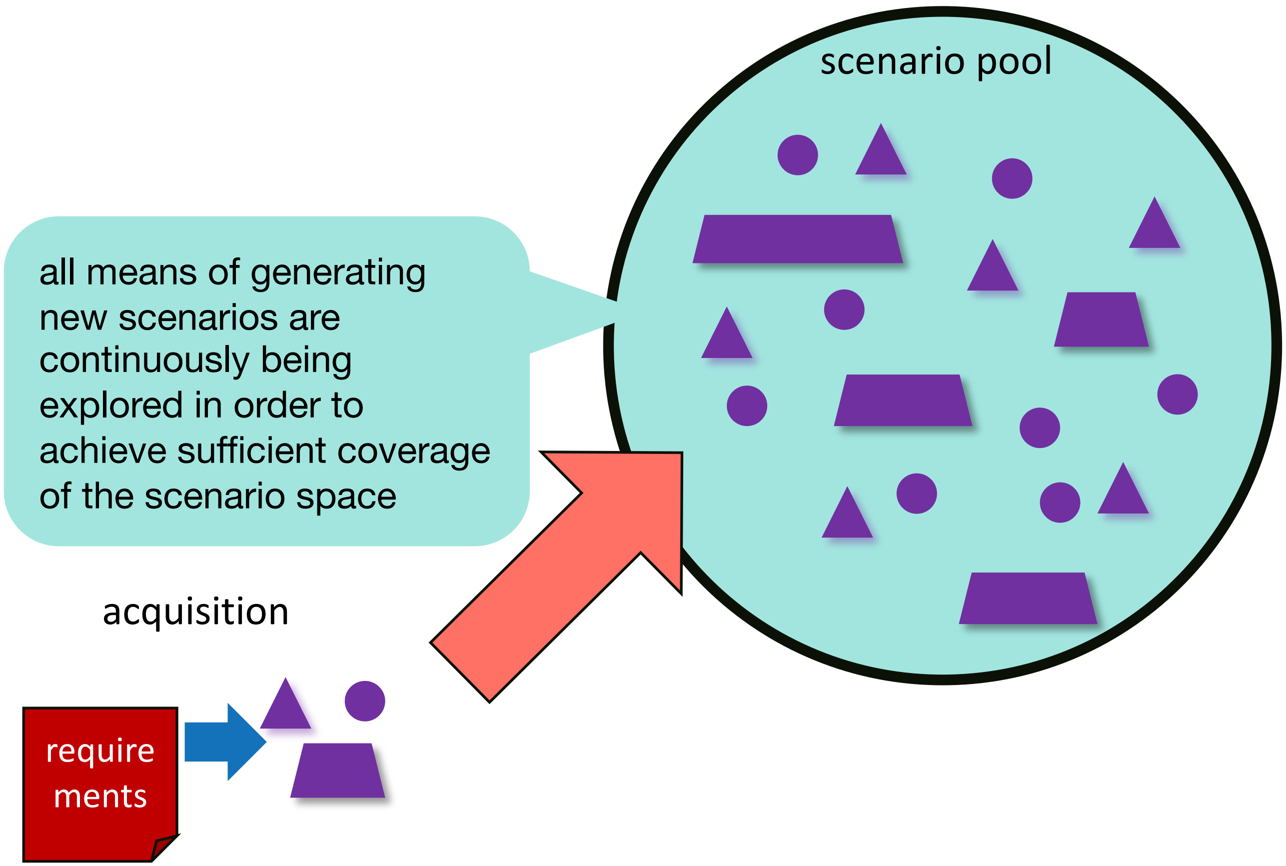


Criticality Focus

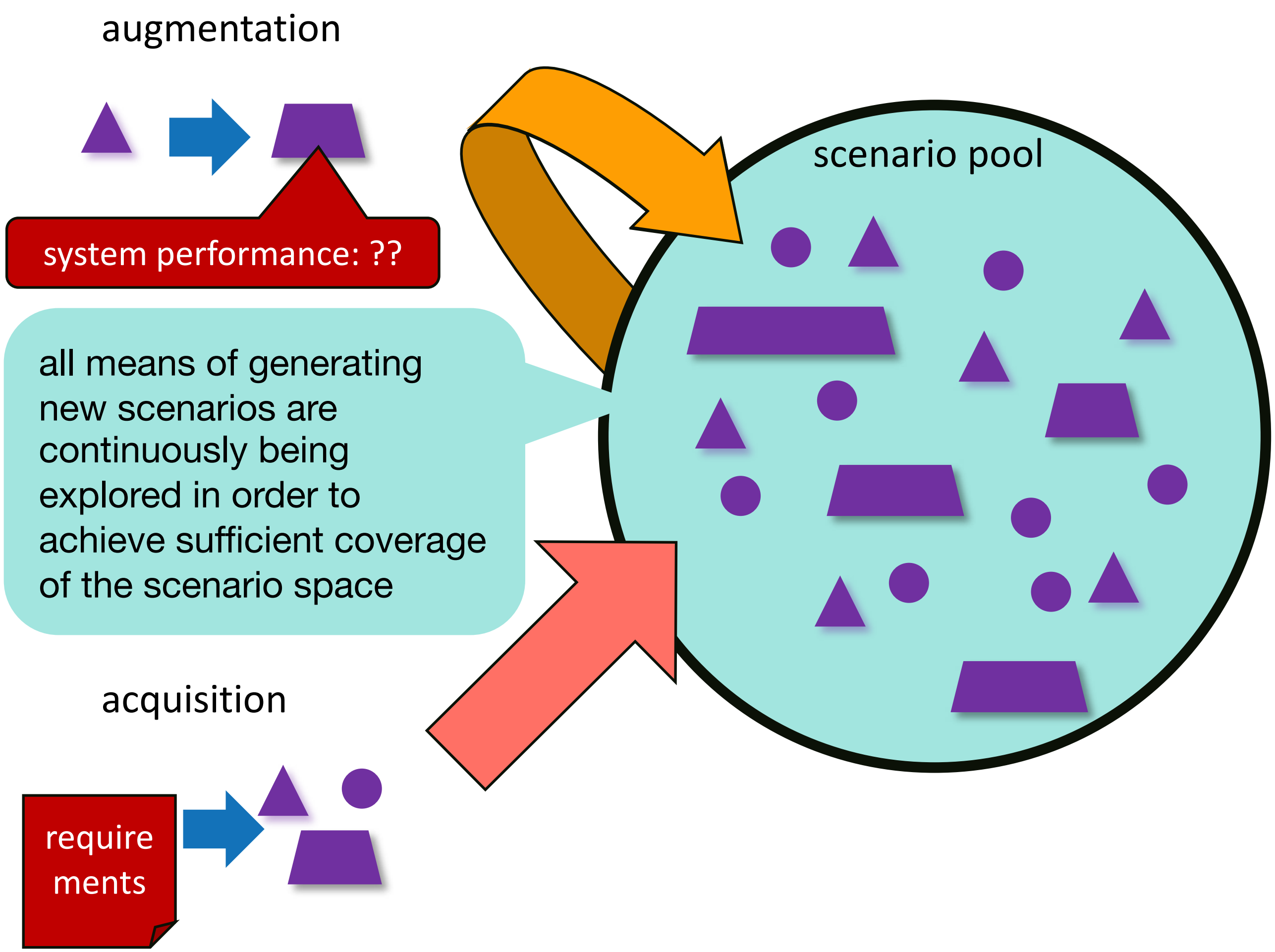
all means of generating new scenarios are continuously being explored in order to achieve sufficient coverage of the scenario space



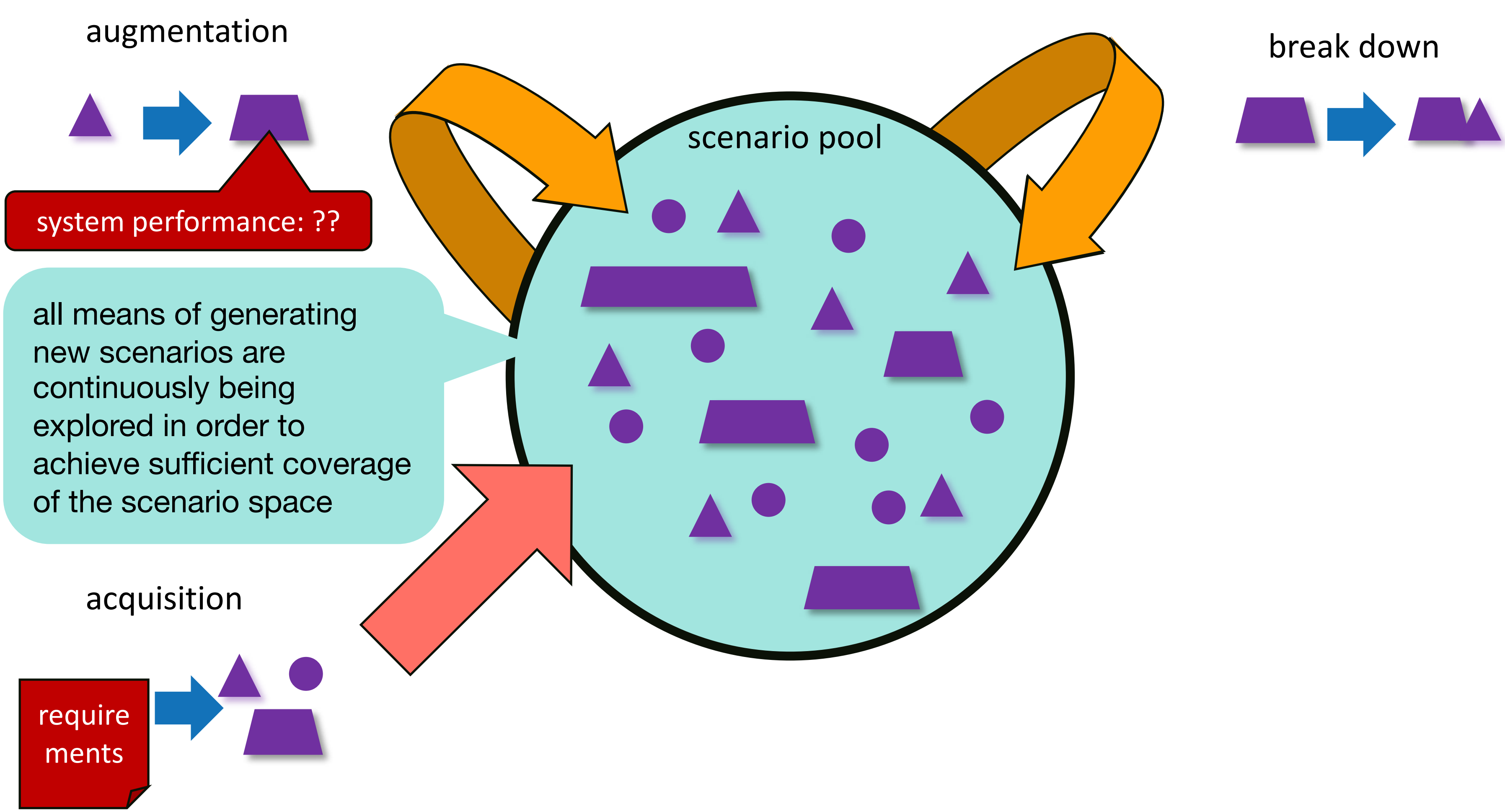
Criticality Focus



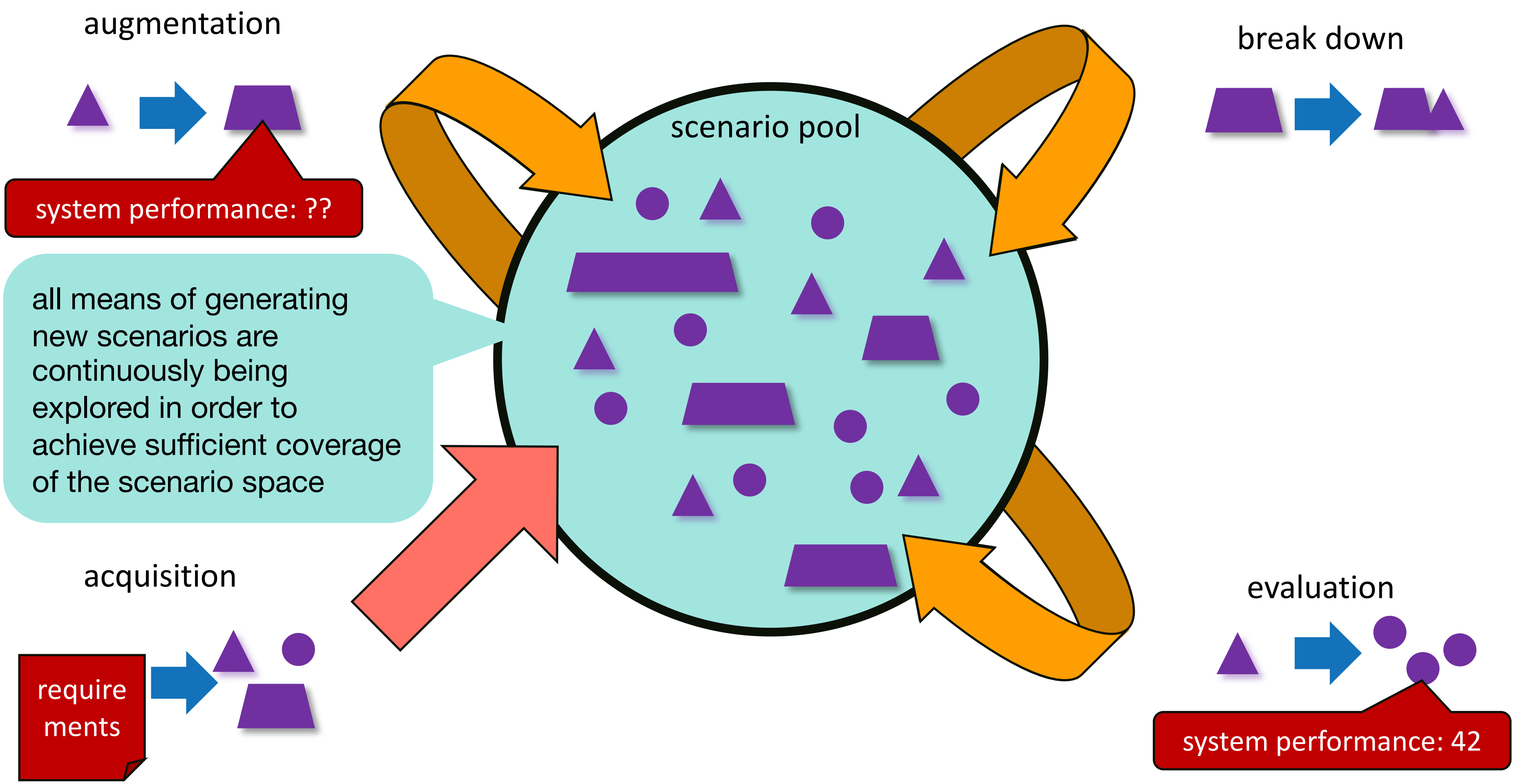
Criticality Focus



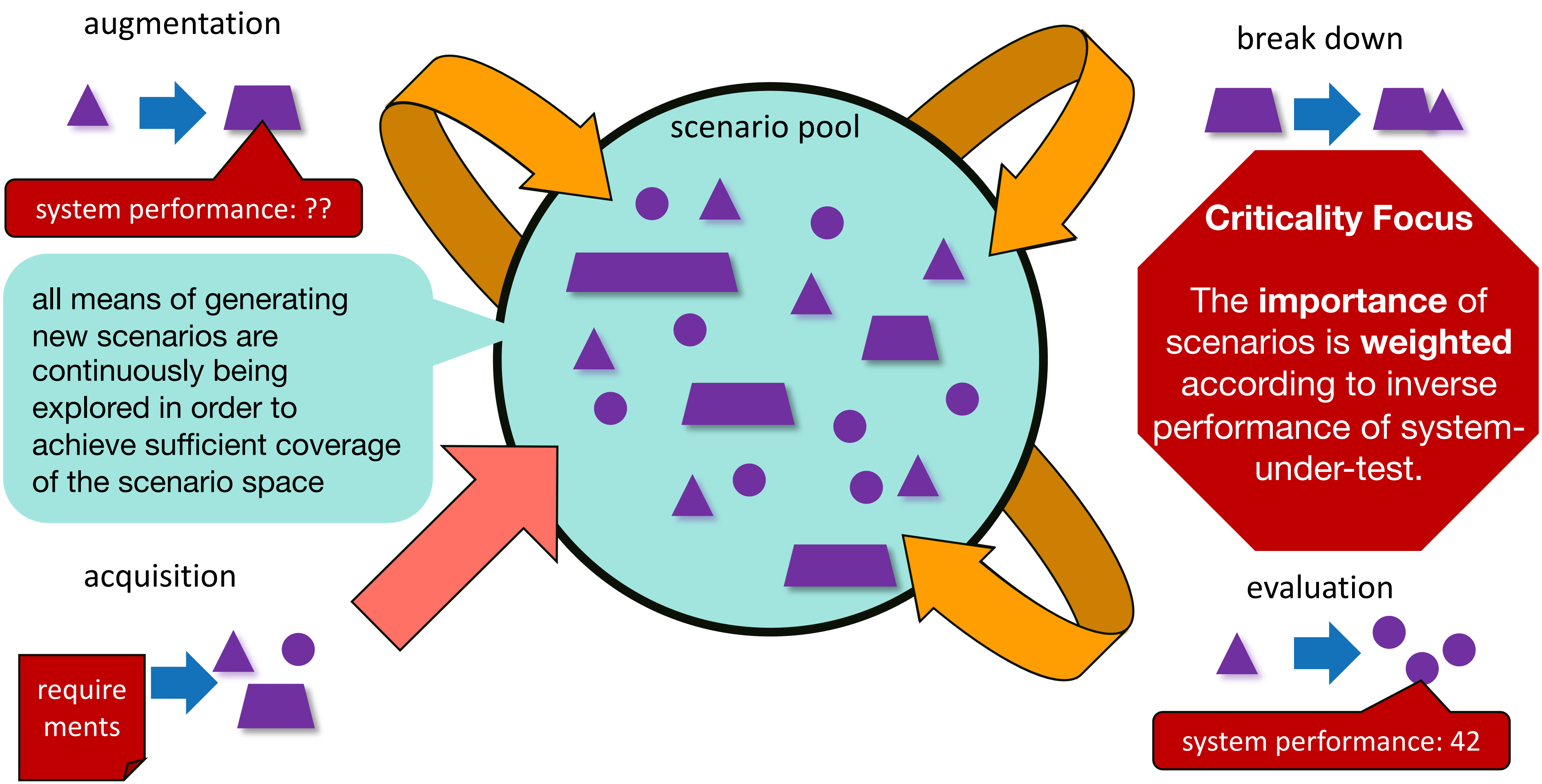
Criticality Focus



Criticality Focus

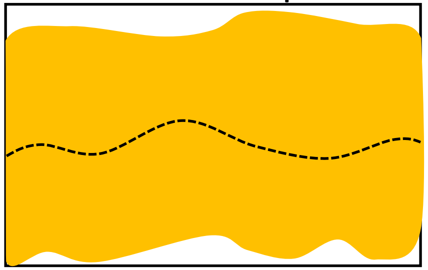


Criticality Focus

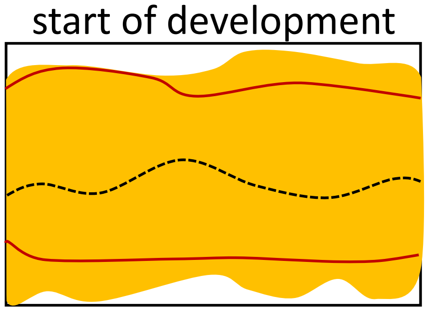


Adaptation Cooldown

start of development



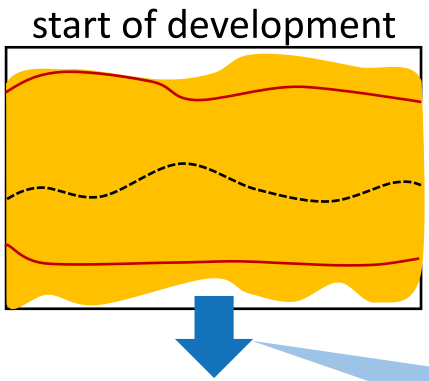
Adaptation Cooldown



off-site adaptation borders

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

Adaptation Cooldown

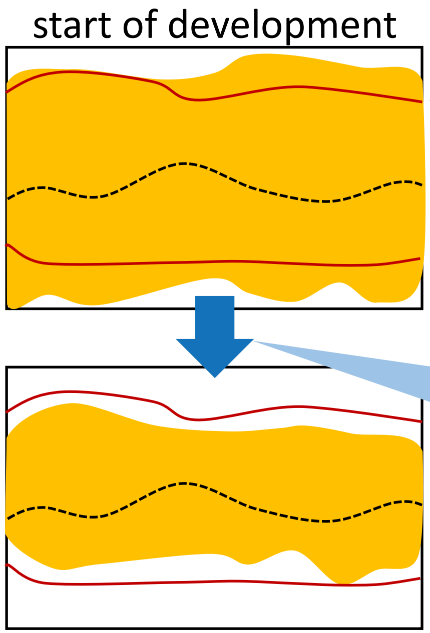


off-site adaptation borders

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



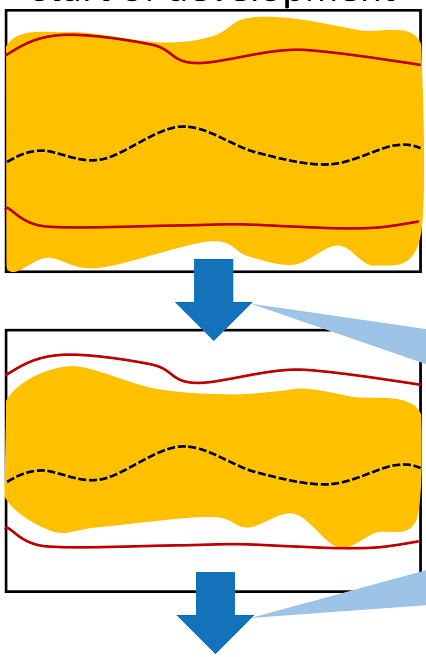
off-site adaptation borders

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

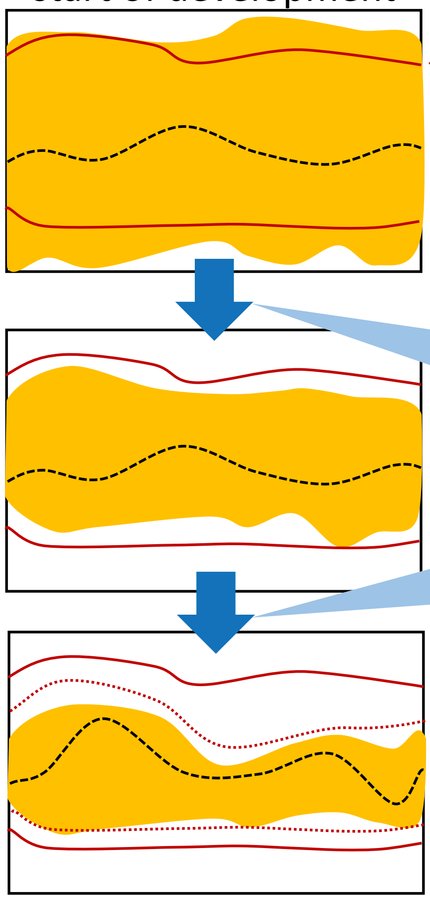
defining the desired limits of the adaptation process for all eventual customer scenarios

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



running product

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

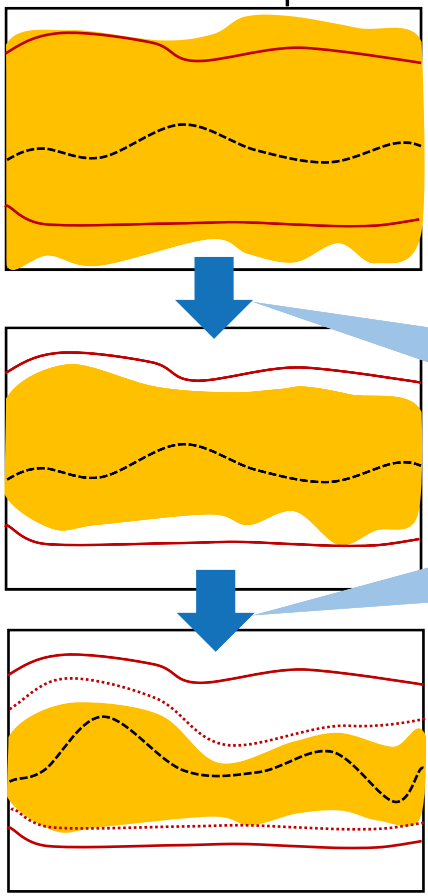
adapting to a single customer‘s specific environment changes the optimal behavior slightly

on-site adaptation borders

during deployment narrower boundaries for adaptation with respect to one customer‘s specific environment may be necessary

Adaptation Cooldown

start of development



running product

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

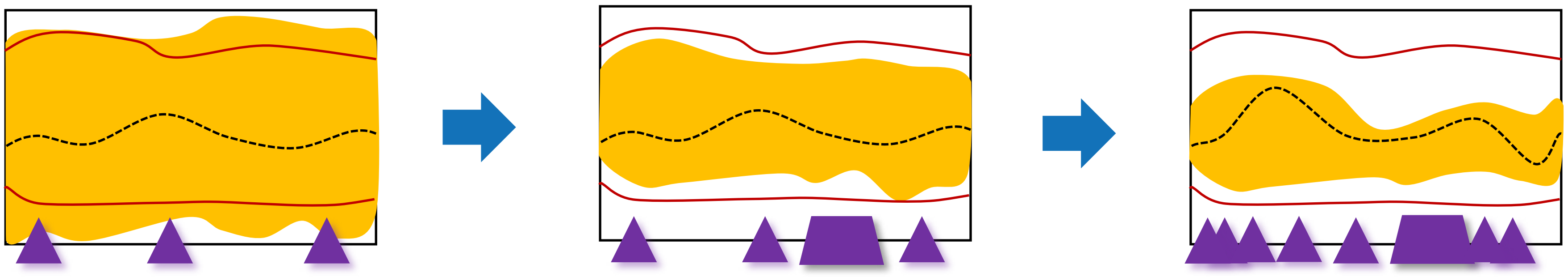
on-site adaptation borders

during deployment narrower boundaries for adaptation with respect to one customer‘s specific environment may be necessary

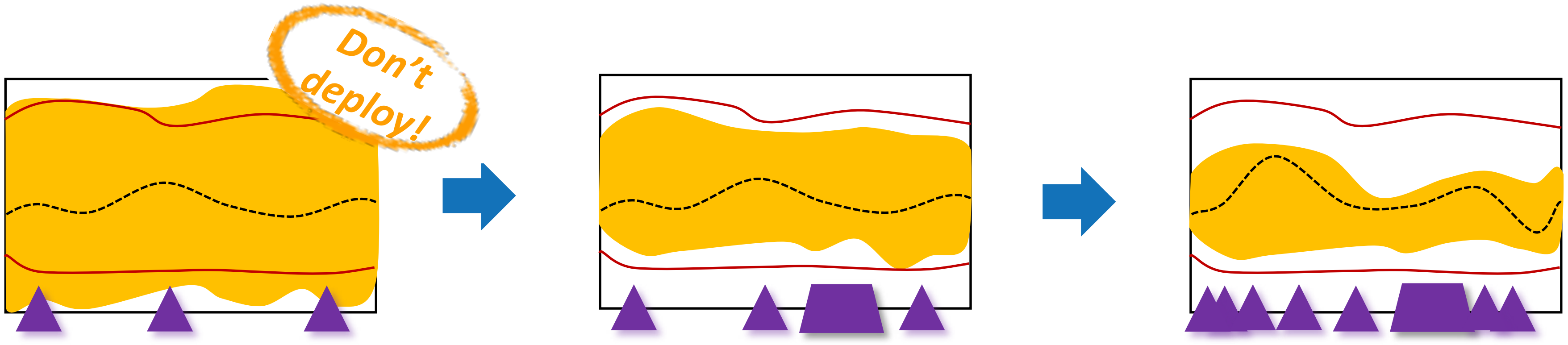
Adaptation Cooldown

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

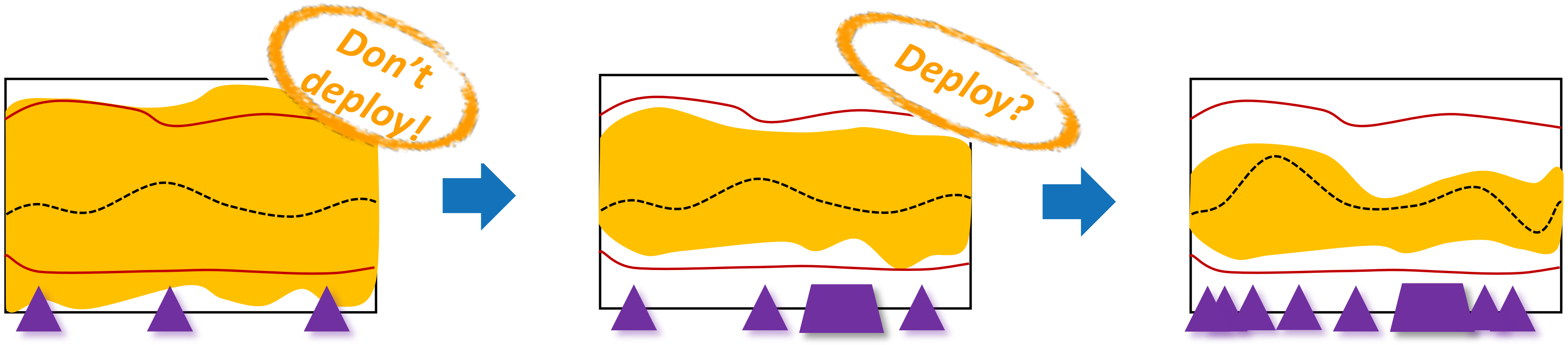
Eternal Deployment



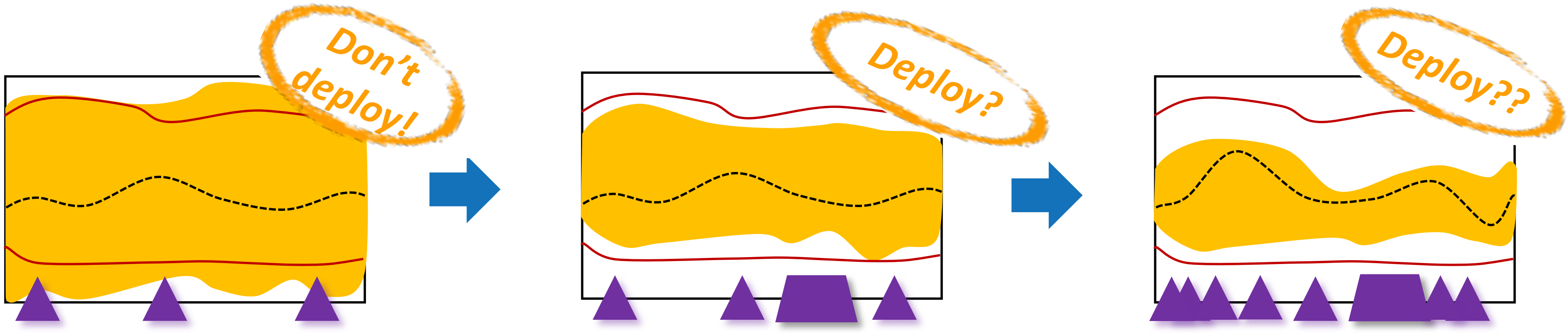
Eternal Deployment



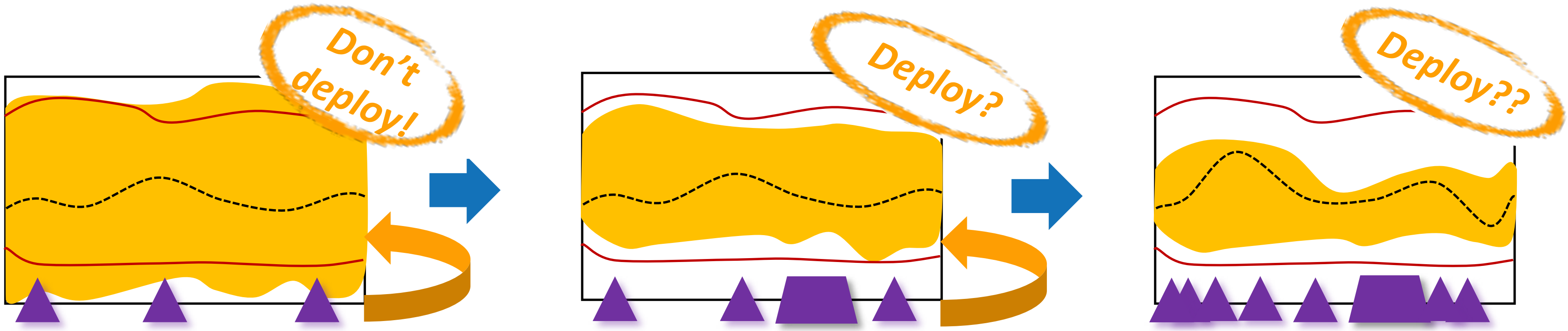
Eternal Deployment



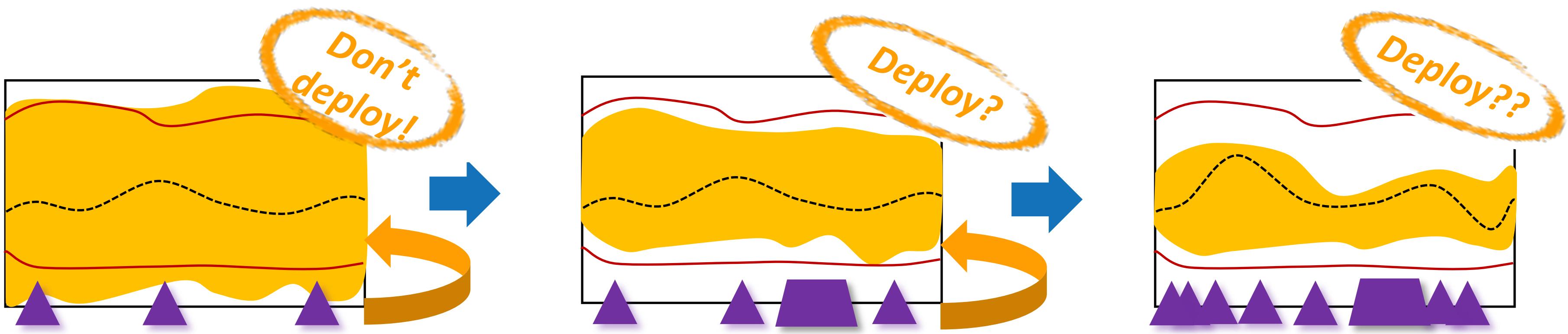
Eternal Deployment



Eternal Deployment

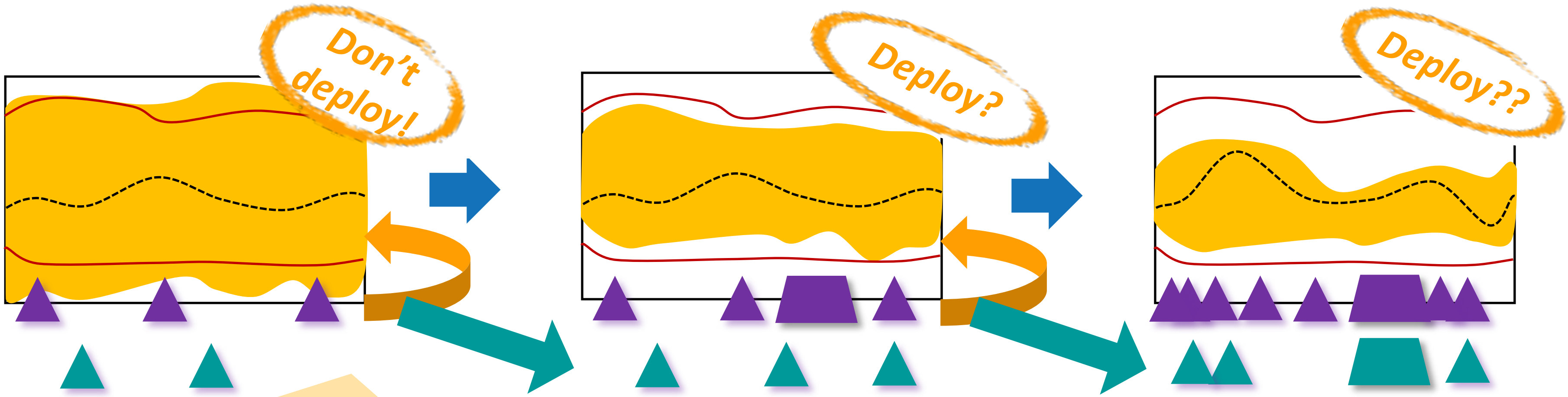


Eternal Deployment



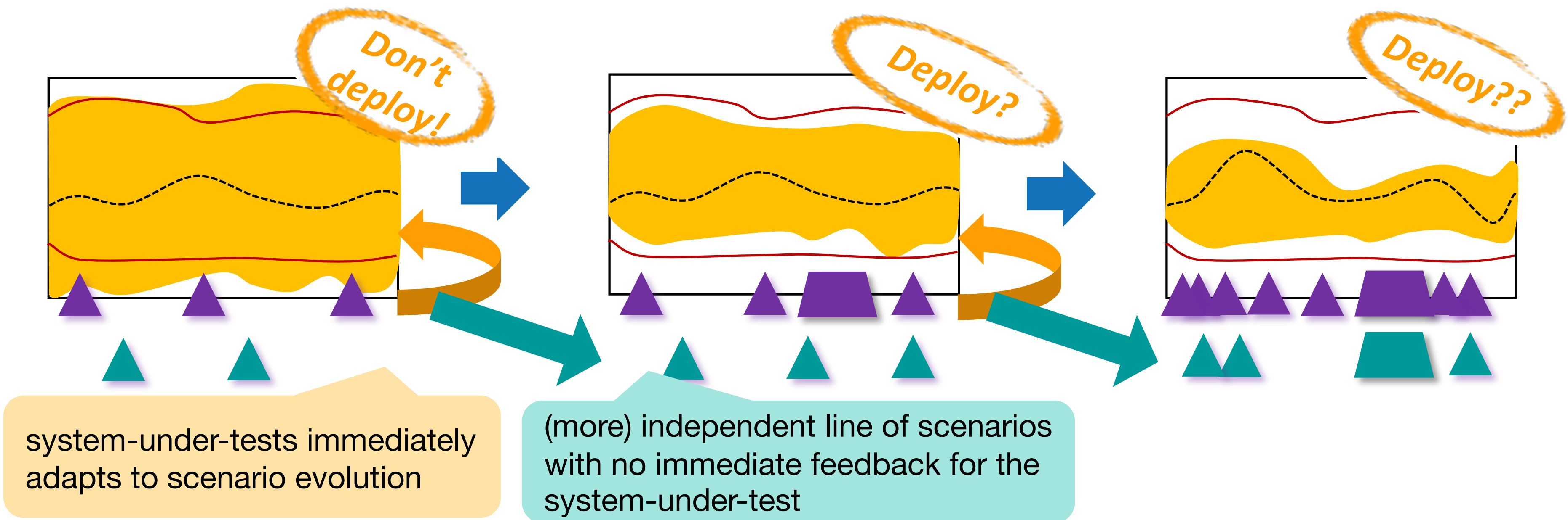
system-under-tests immediately adapts to scenario evolution

Eternal Deployment

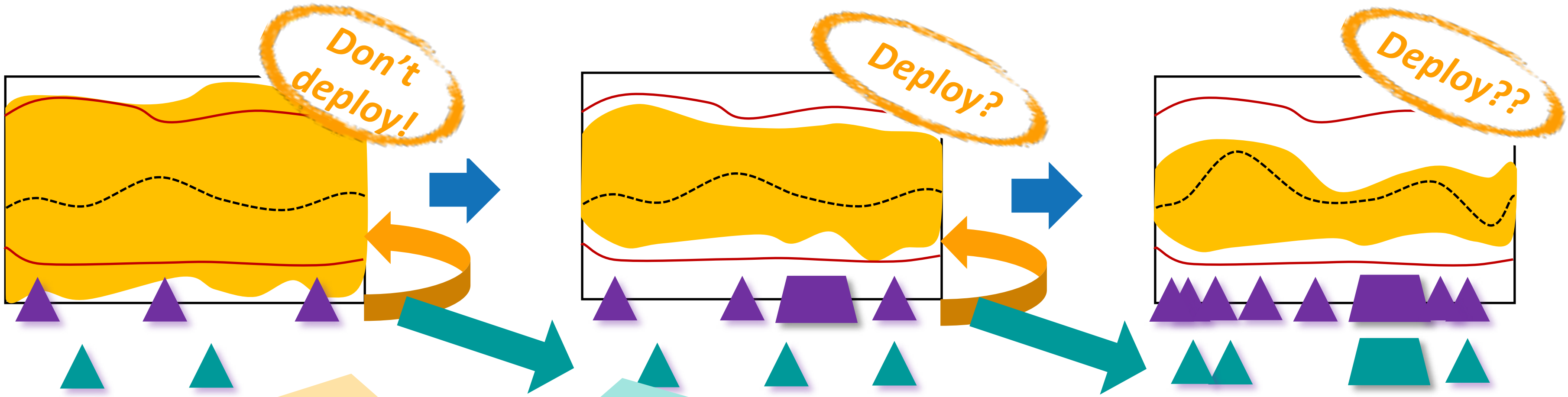


system-under-tests immediately adapts to scenario evolution

Eternal Deployment



Eternal Deployment



system-under-tests immediately adapts to scenario evolution

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

Deploy All

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

Oscar Nierstrasz, Marcus Denker, Tudor Gîrba, Adrian Lienhard, David Röthlisberger (2008). Change-enabled software systems. In Software-Intensive Systems and New Computing Paradigms. Springer, Berlin, Heidelberg.

Tools for a New Framework

Criticality Focus

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

Adaptation Cooldown

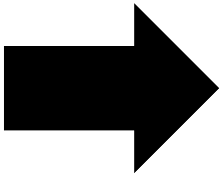
As system development progresses, the space of **possible behavior** available to the adaptation mechanism **decreases.**

Deploy All

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

The Big Picture

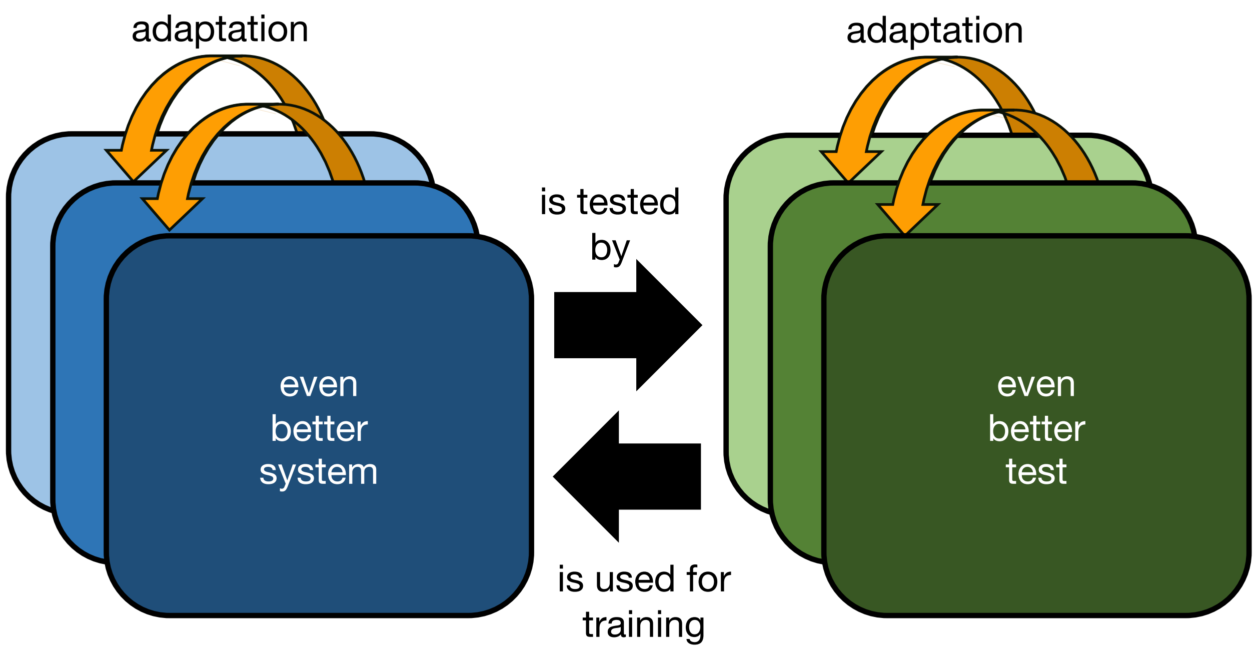
The Big Picture



We need AI to adequately control AI.

Where to go from here?

Where to go from here?

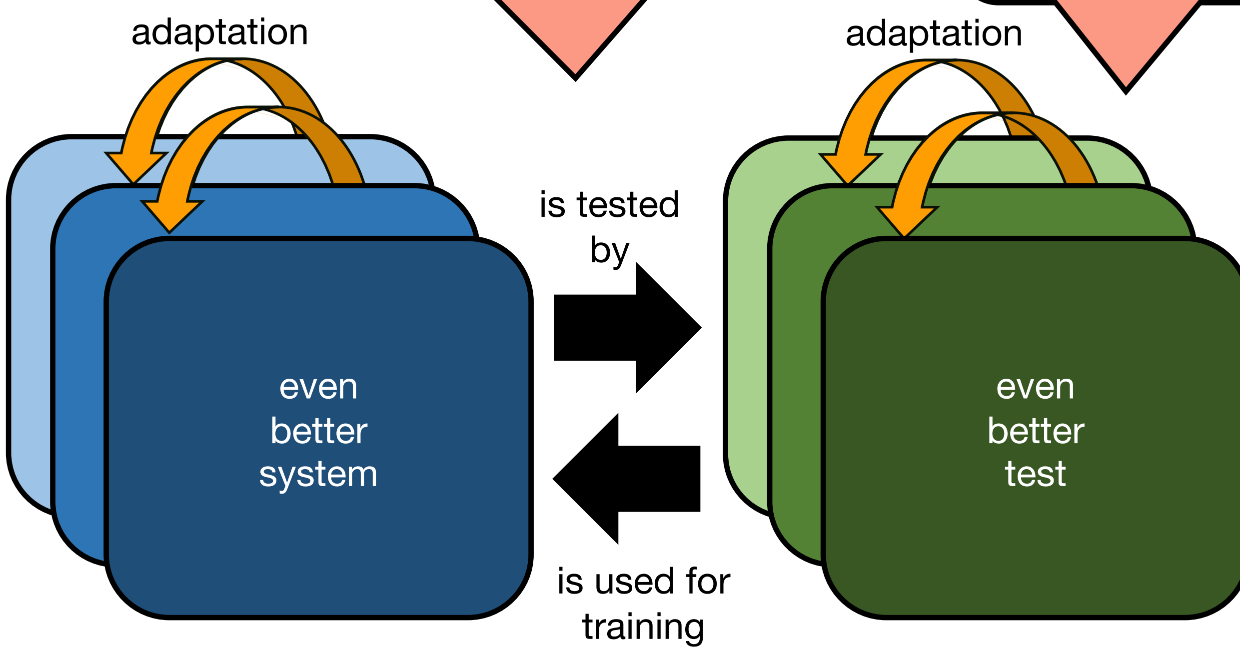


Where to go from here?

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.

AI and the Compute Method

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**.”

Rich Sutton.
The Bitter Lesson.
www.incompleteideas.net/IncIdeas/BitterLesson.html

AI and the Compute Method

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

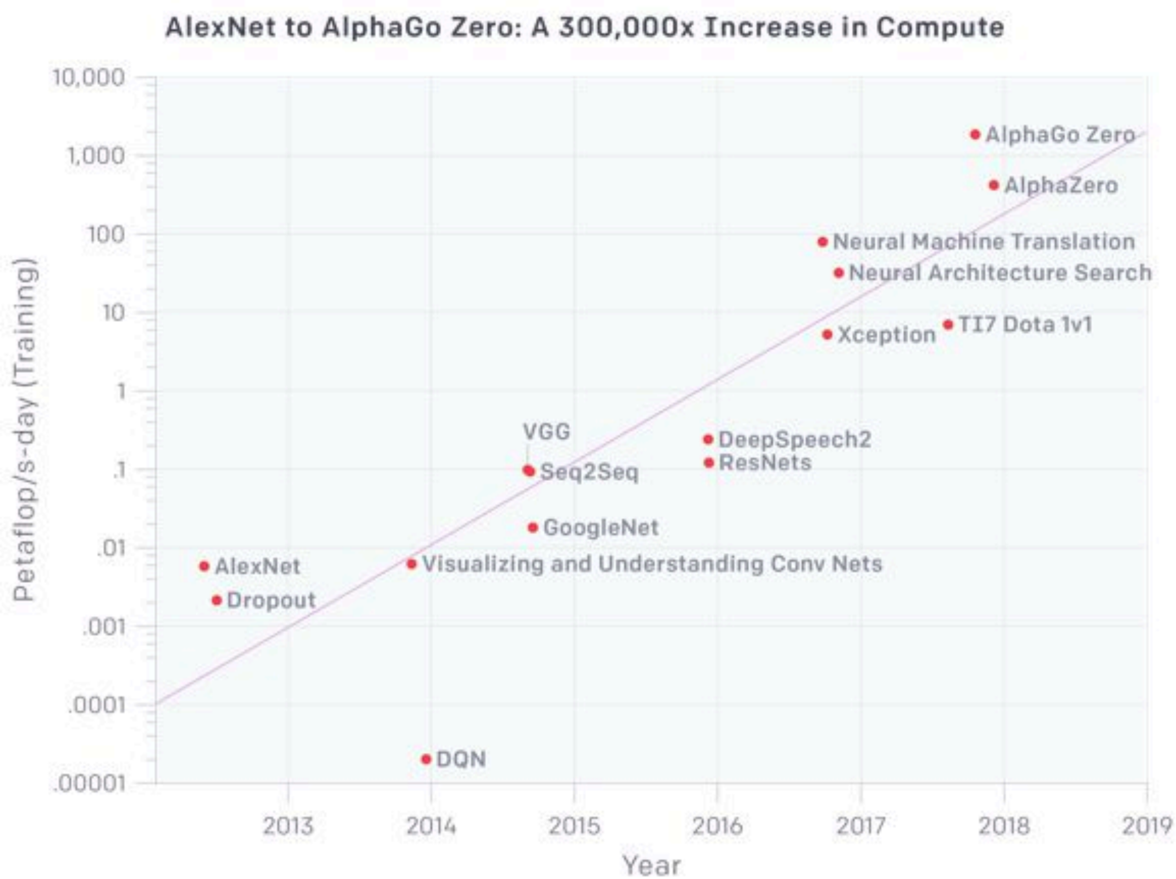
3) in the long run it plateaus and even **inhibits further progress**, and

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.”

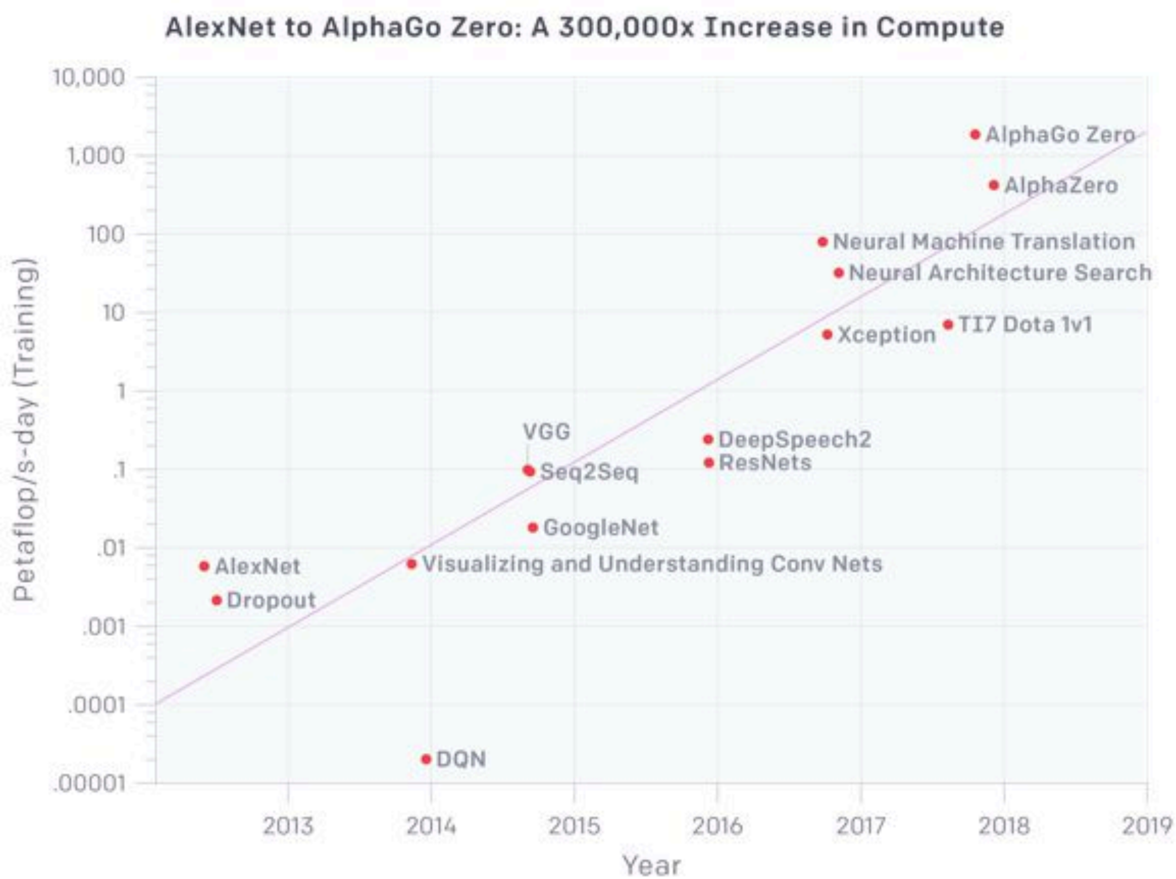
Rich Sutton.
The Bitter Lesson.
www.incompleteideas.net/IncIdeas/BitterLesson.html

Computation Power used in AI



Dario Amodei and Danny Hernandez. AI and Compute. openai.com/blog/ai-and-compute/

Computation Power used in AI



"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)."

Dario Amodei and Danny Hernandez. AI and Compute. openai.com/blog/ai-and-compute/

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

Quantum Computing?

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

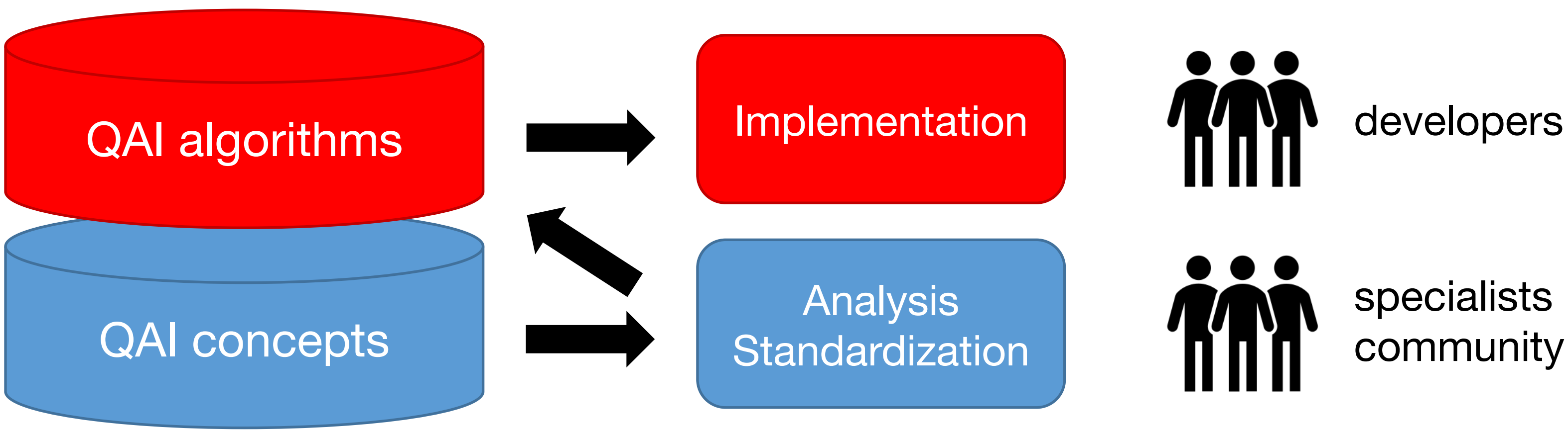
AI Algorithms

Quantum Platform

The PlanQK consortium.
planqk.de

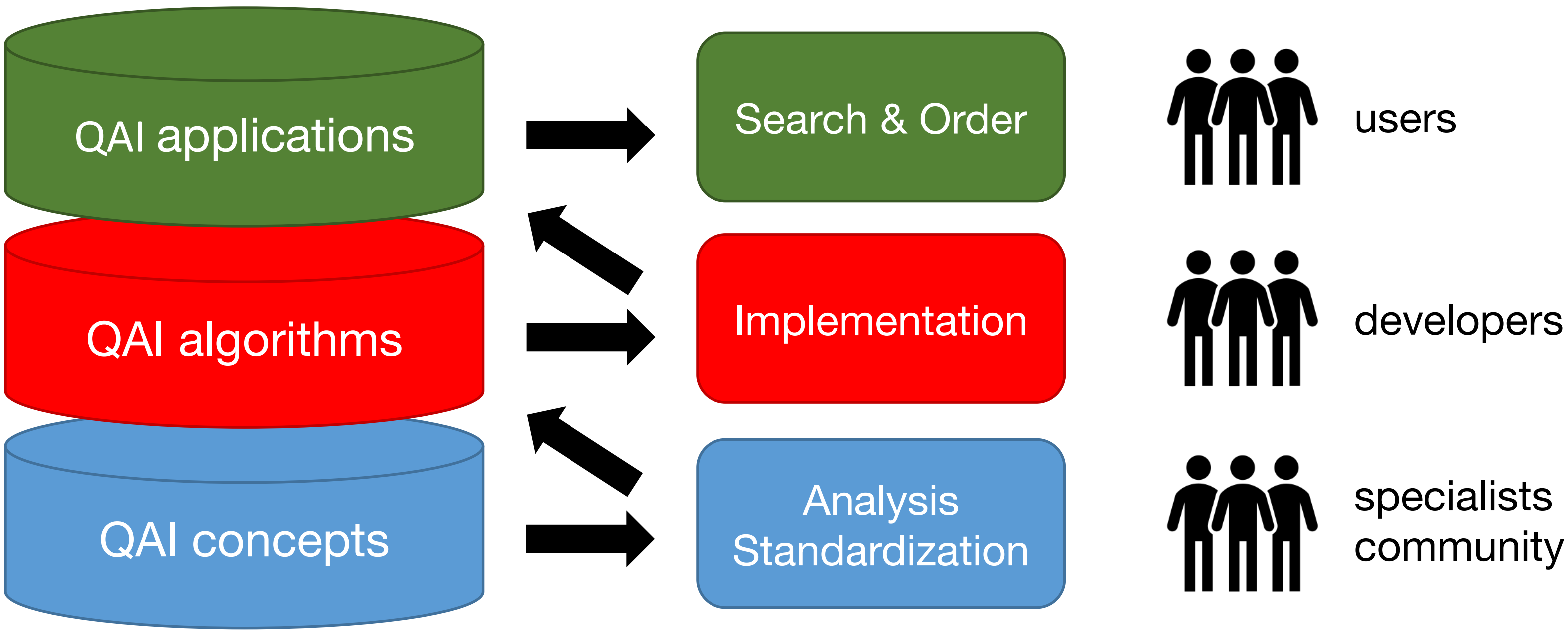
The PlanQK Platform

The PlanQK Platform



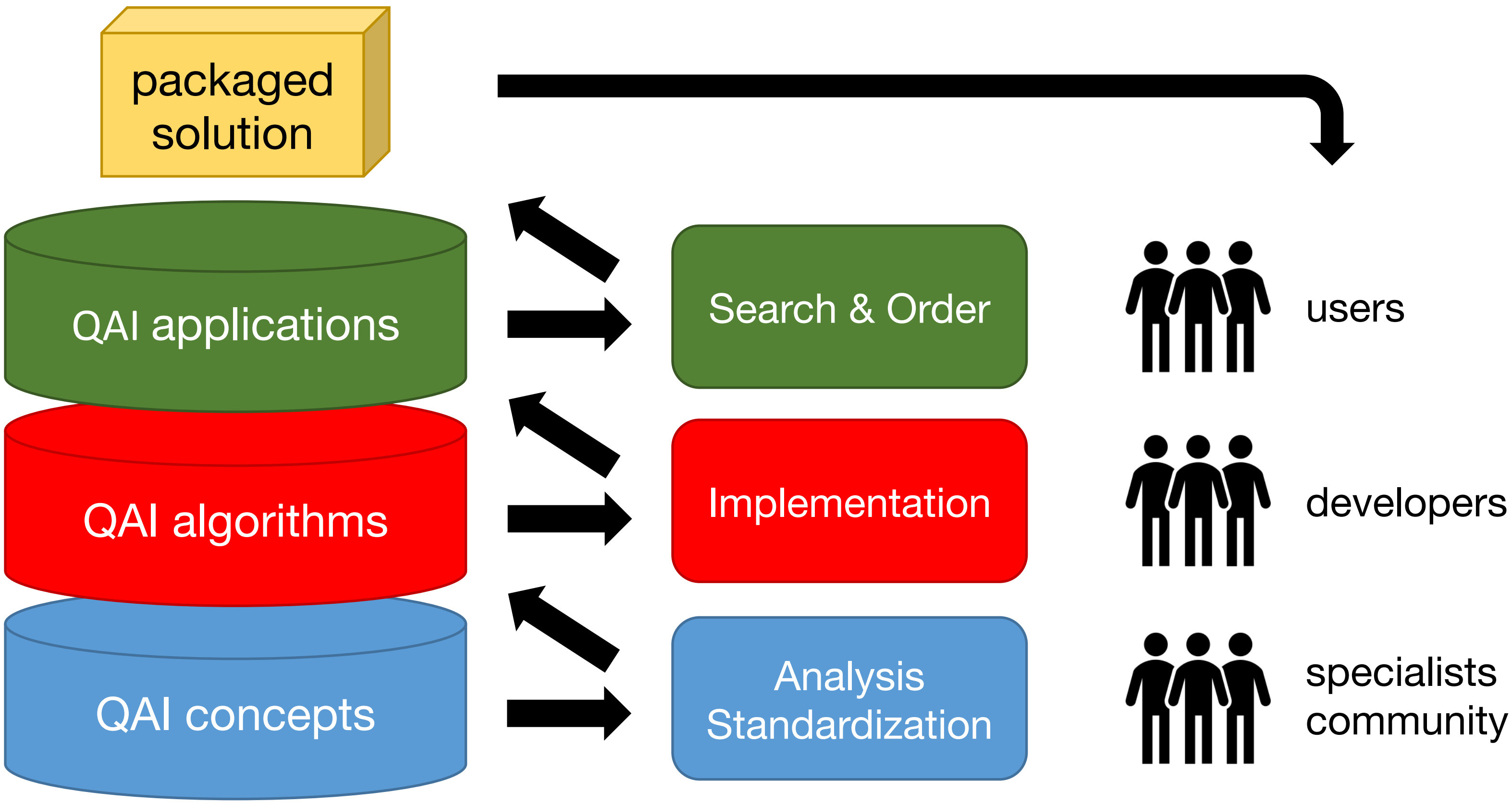
The PlanQK consortium.
planqk.de

The PlanQK Platform



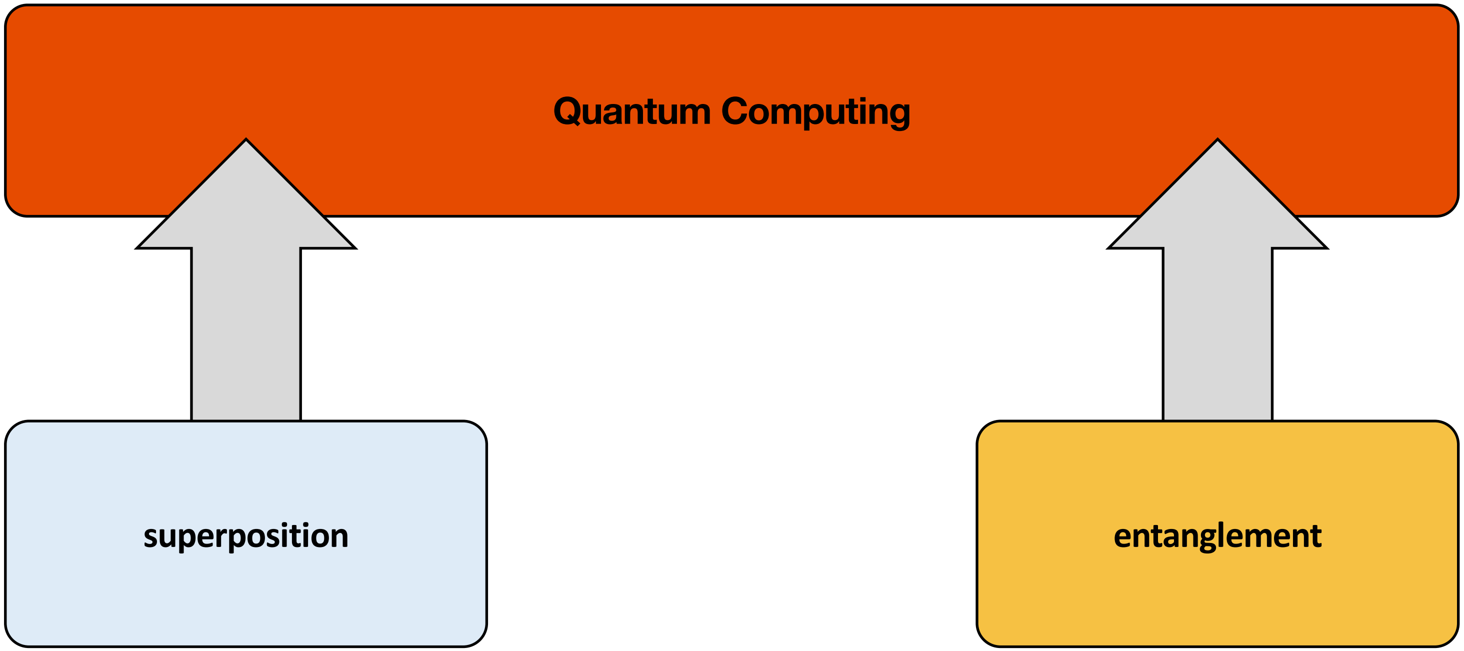
The PlanQK consortium.
planqk.de

The PlanQK Platform



The PlanQK consortium.
planqk.de

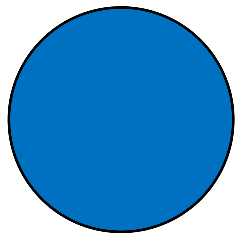
So what else is new?



Superposition

classical physics

particle



Superposition

classical physics

particle

spin

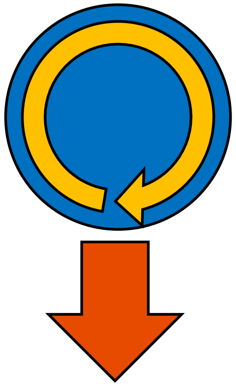
Superposition

classical physics

particle

spin

measure spin



Superposition

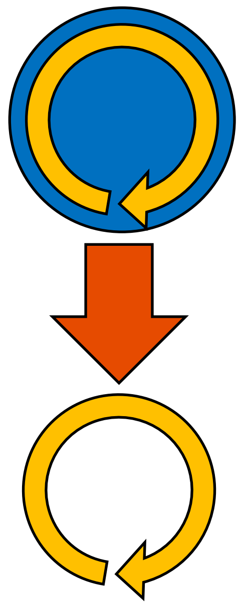
classical physics

particle

spin

measure spin

measured spin



Superposition

classical physics

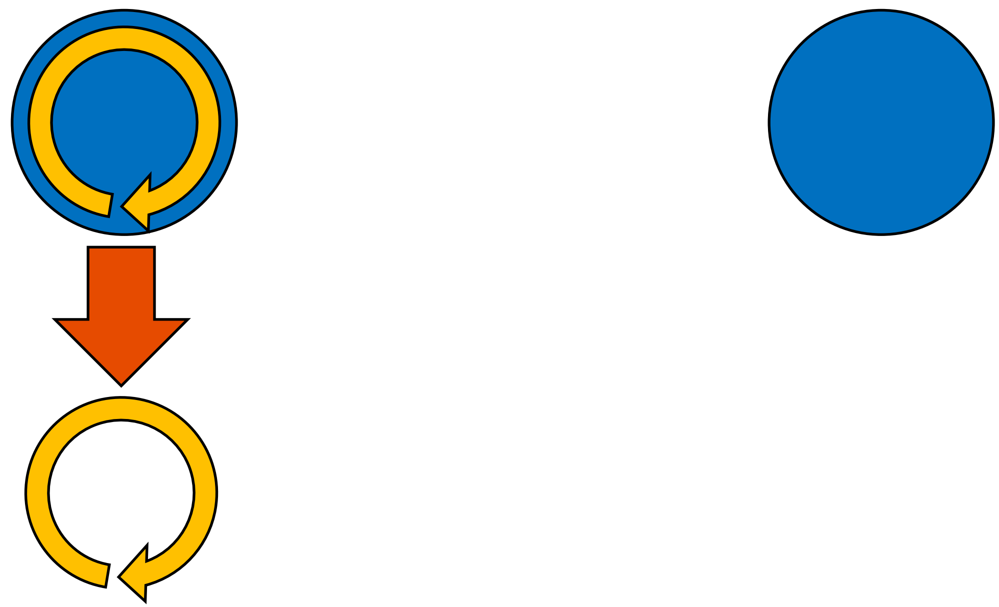
quantum physics

particle

spin

measure spin

measured spin



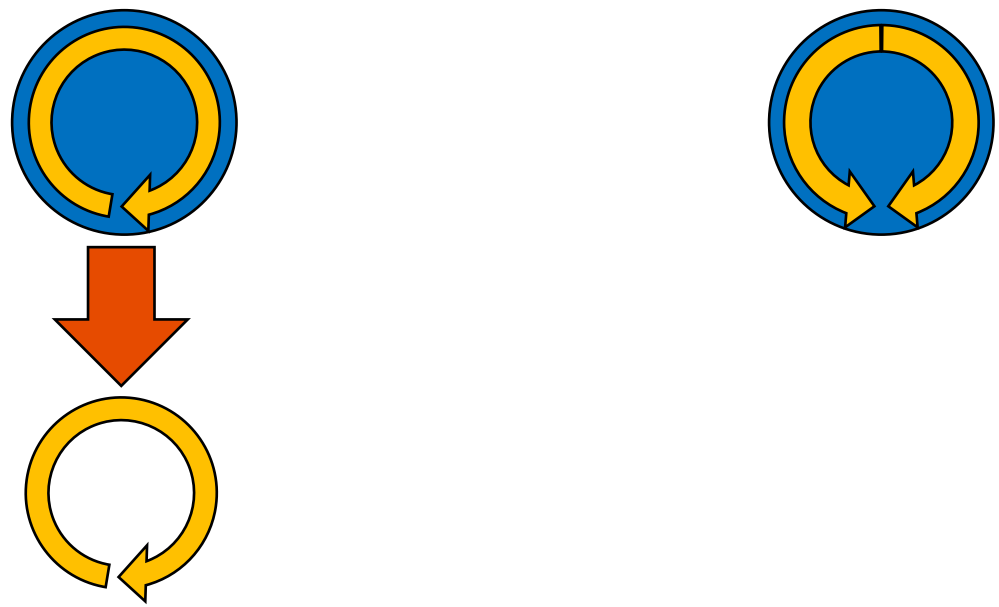
Superposition

classical physics

quantum physics

particle

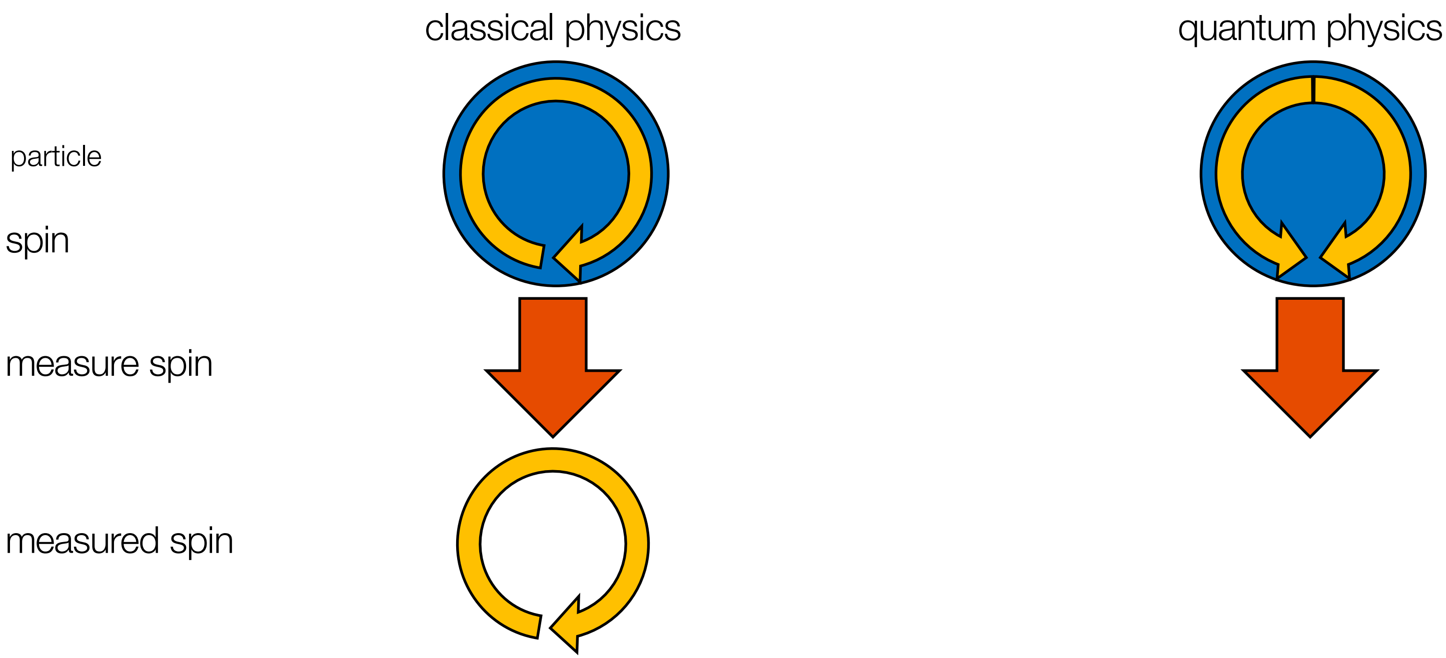
spin



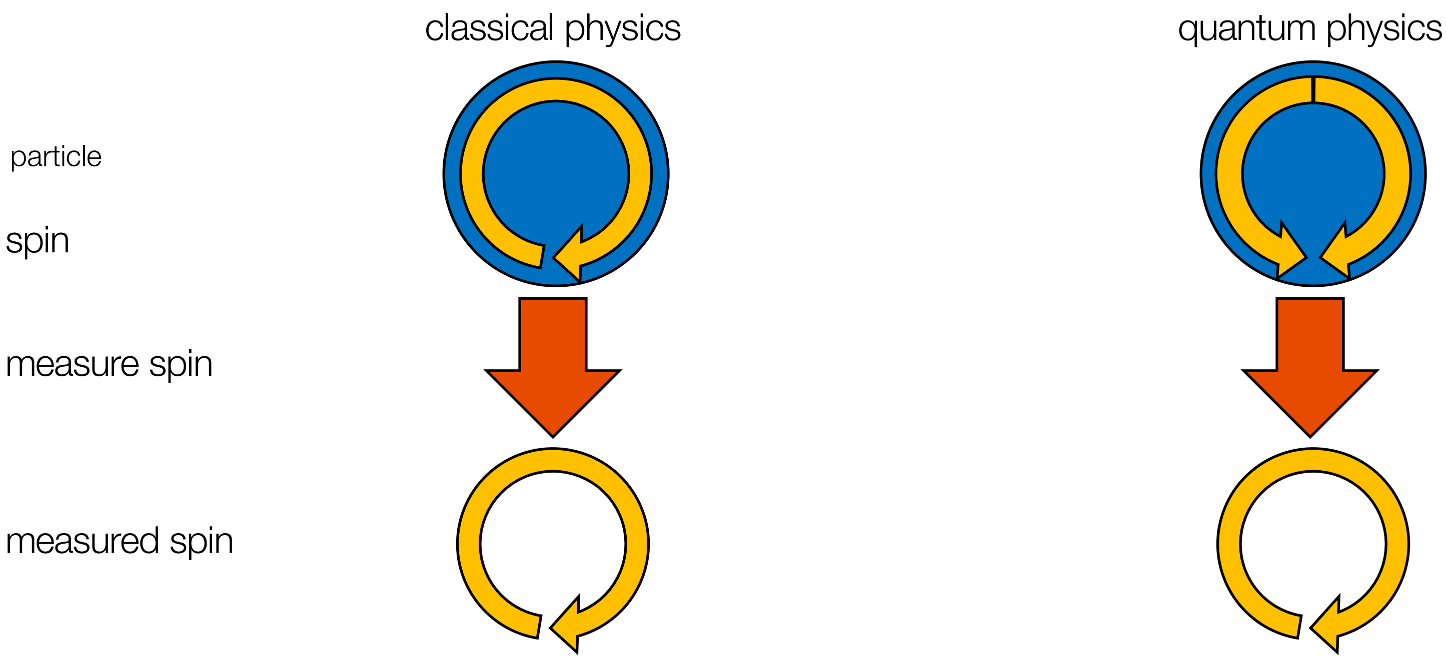
measure spin

measured spin

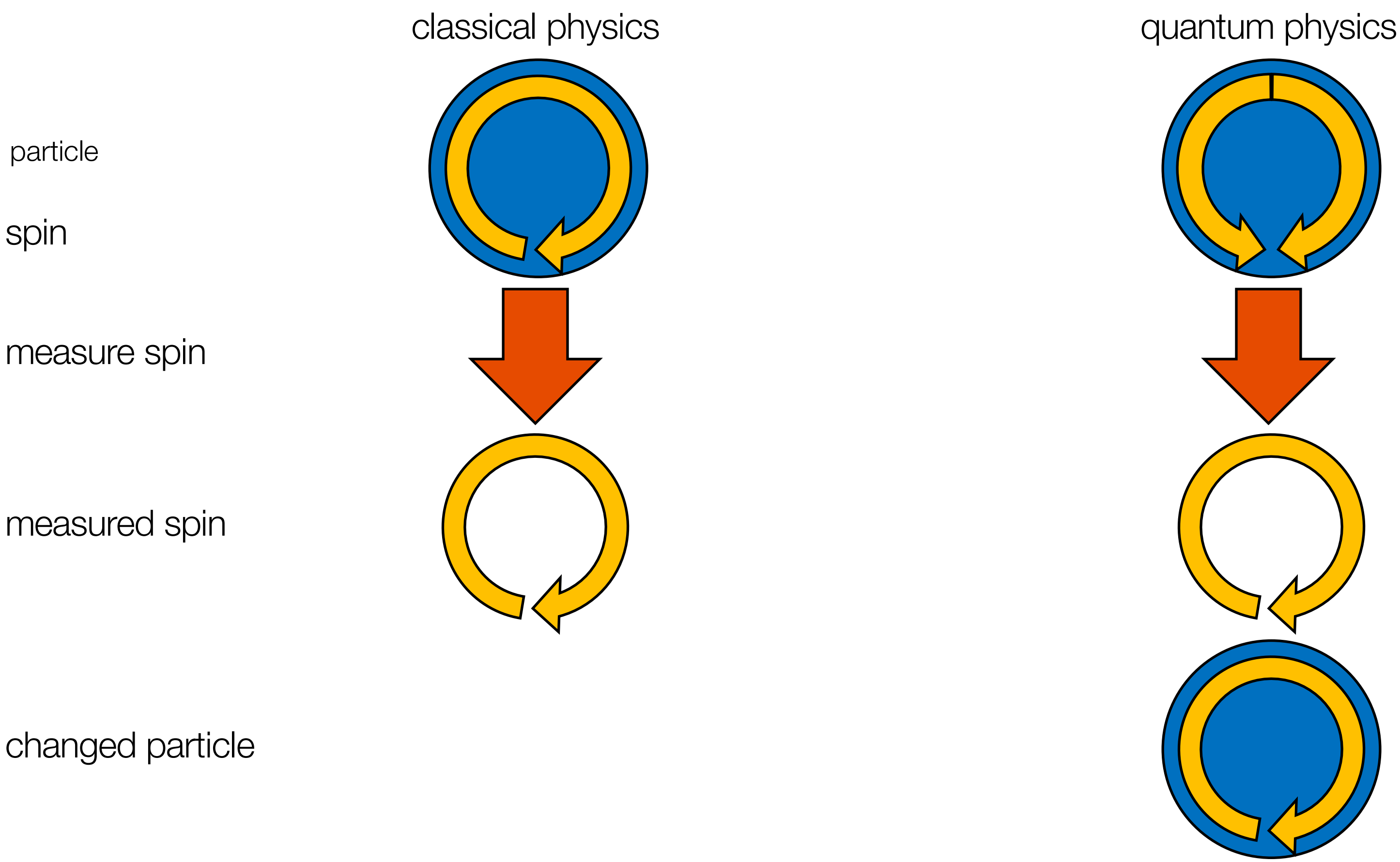
Superposition



Superposition



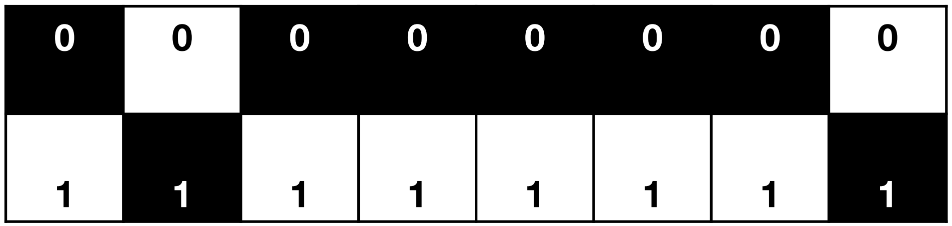
Superposition



Registers

0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1

Registers



ASCII letter A

Superposition on Registers

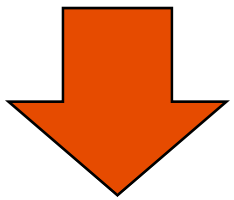
0 50%	**0** 50%	**0** 50%	**0** 50%	**0** 50%	**0** 50%	**0** 50%	**0** 50%
50% **1**	50% **1**	50% **1**	50% **1**	50% **1**	50% **1**	50% **1**	50% **1**

all ASCII letters
at the same time

Superposition on Registers

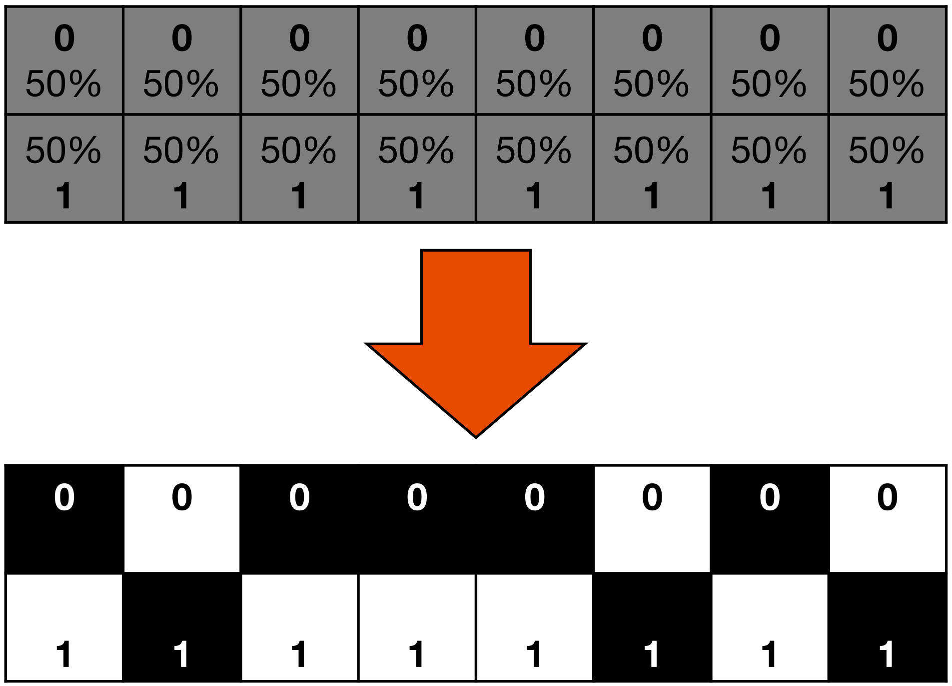
0 50%	**0** 50%	**0** 50%	**0** 50%	**0** 50%	**0** 50%	**0** 50%	**0** 50%
50% **1**	50% **1**	50% **1**	50% **1**	50% **1**	50% **1**	50% **1**	50% **1**

all ASCII letters
at the same time



measuring

Superposition on Registers

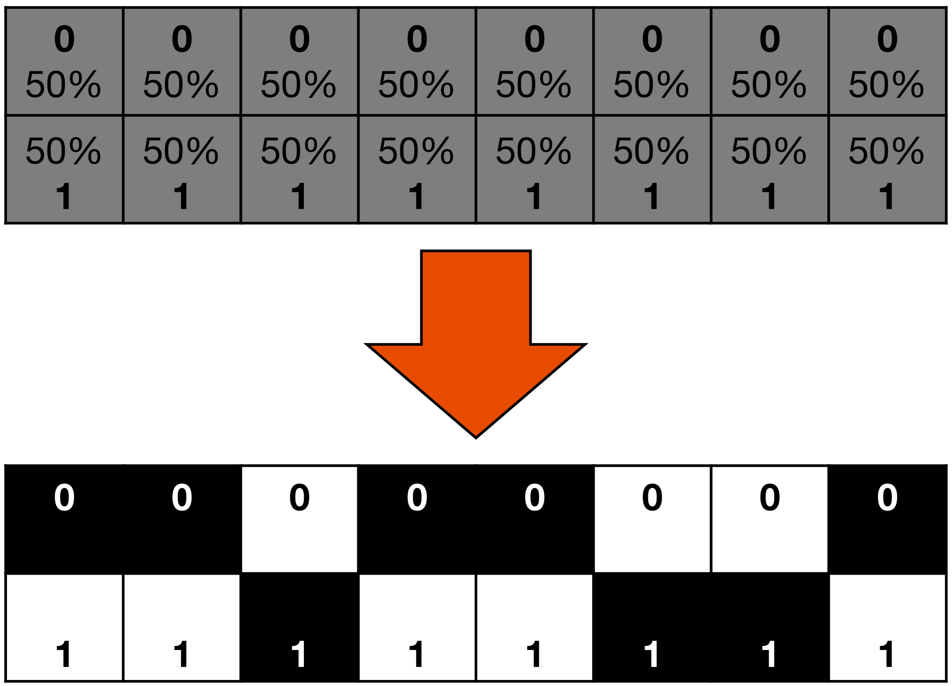


all ASCII letters
at the same time

measuring

ASCII letter E with
probability 1/256

Superposition on Registers

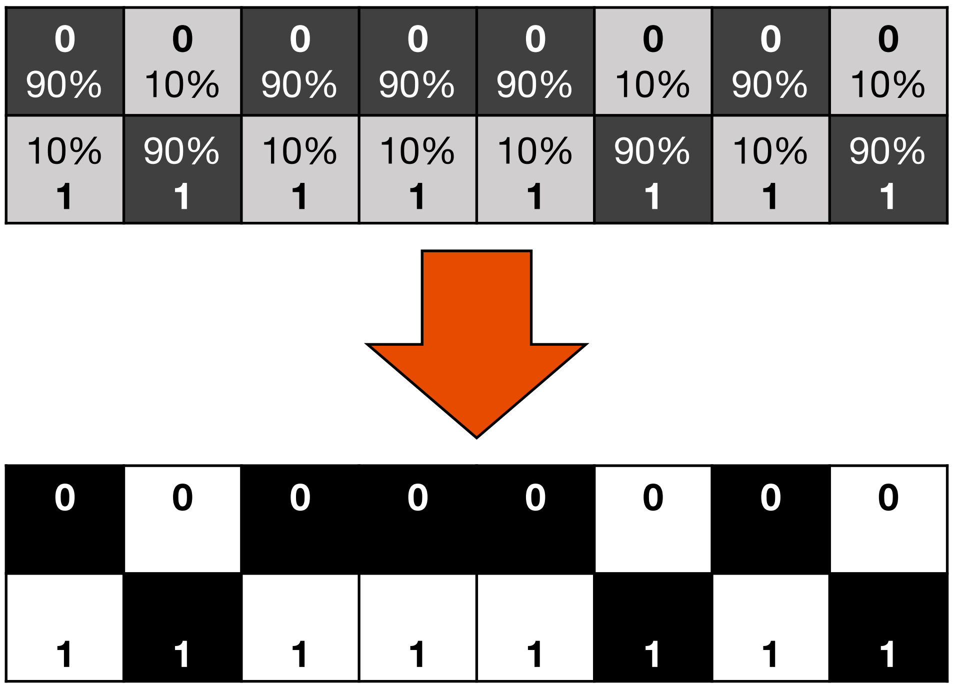


all ASCII letters
at the same time

measuring

ASCII letter & with
probability 1/256

Superposition on Registers



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

measuring

ASCII letter E with
probability 0.43

Entanglement

multiple quantum particles

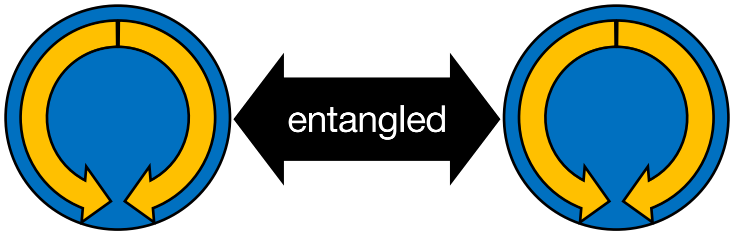
measure single spin

measured spin

changed particles

Entanglement

multiple quantum particles



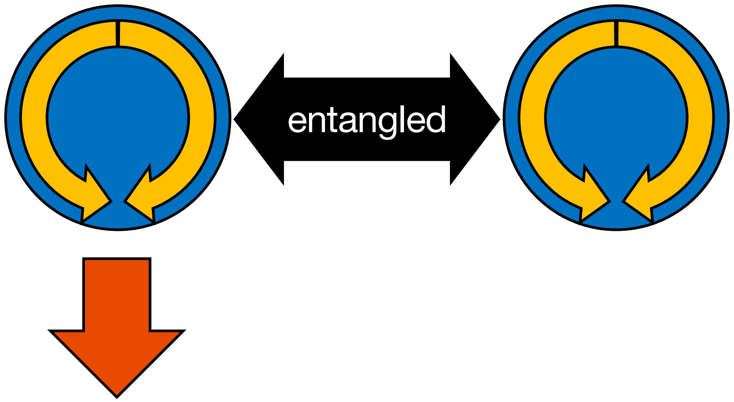
measure single spin

measured spin

changed particles

Entanglement

multiple quantum particles



measure single spin

measured spin

changed particles

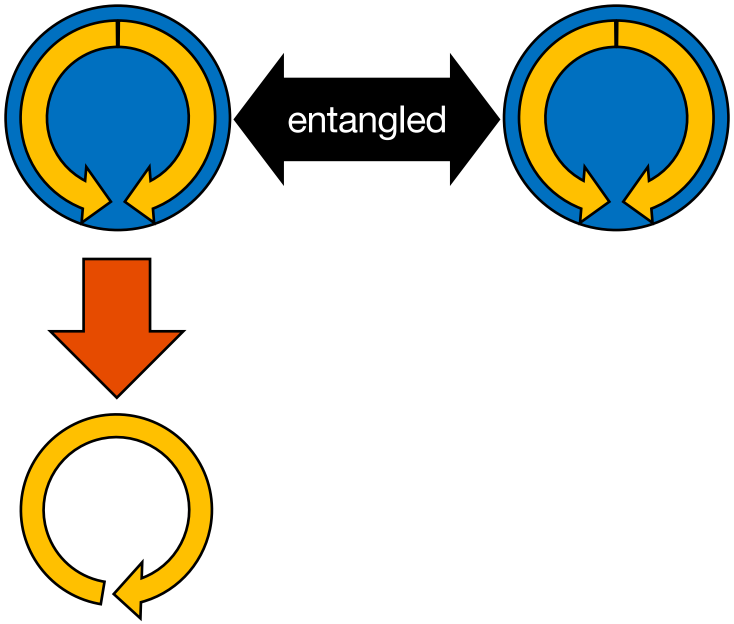
Entanglement

multiple quantum particles

measure single spin

measured spin

changed particles



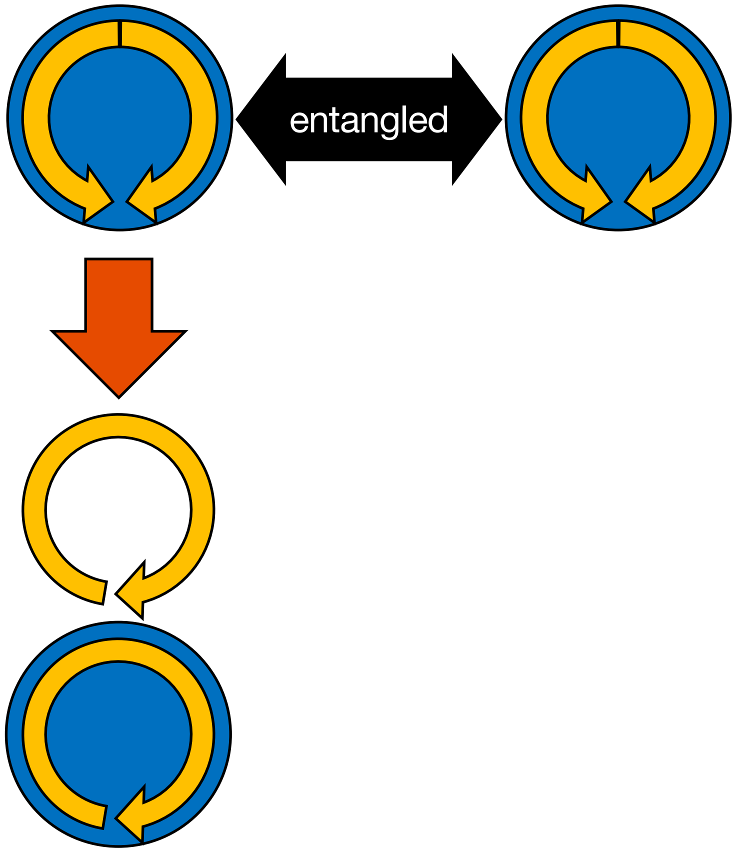
Entanglement

multiple quantum particles

measure single spin

measured spin

changed particles



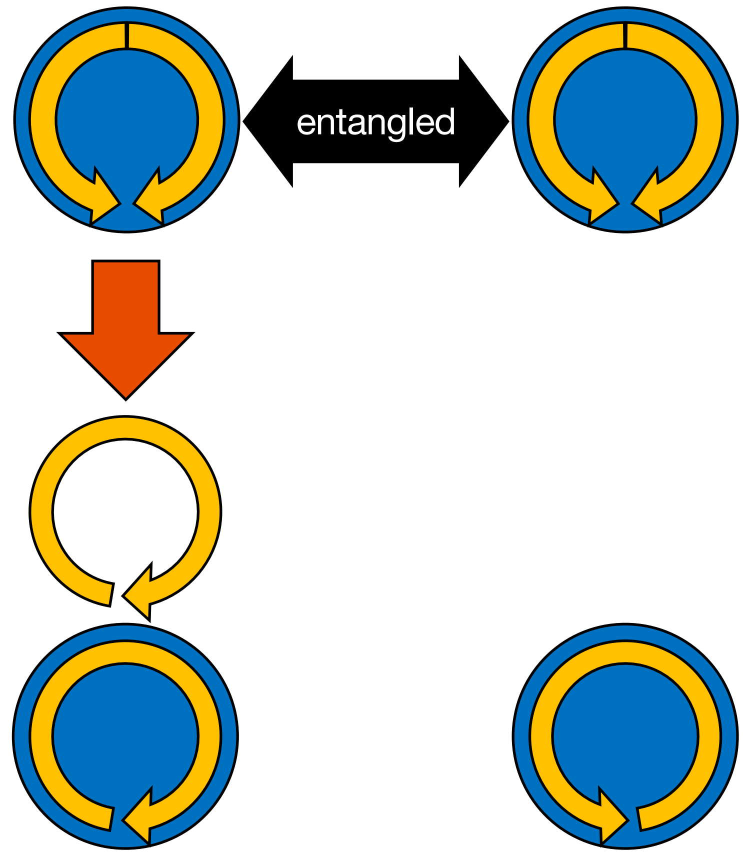
Entanglement

multiple quantum particles

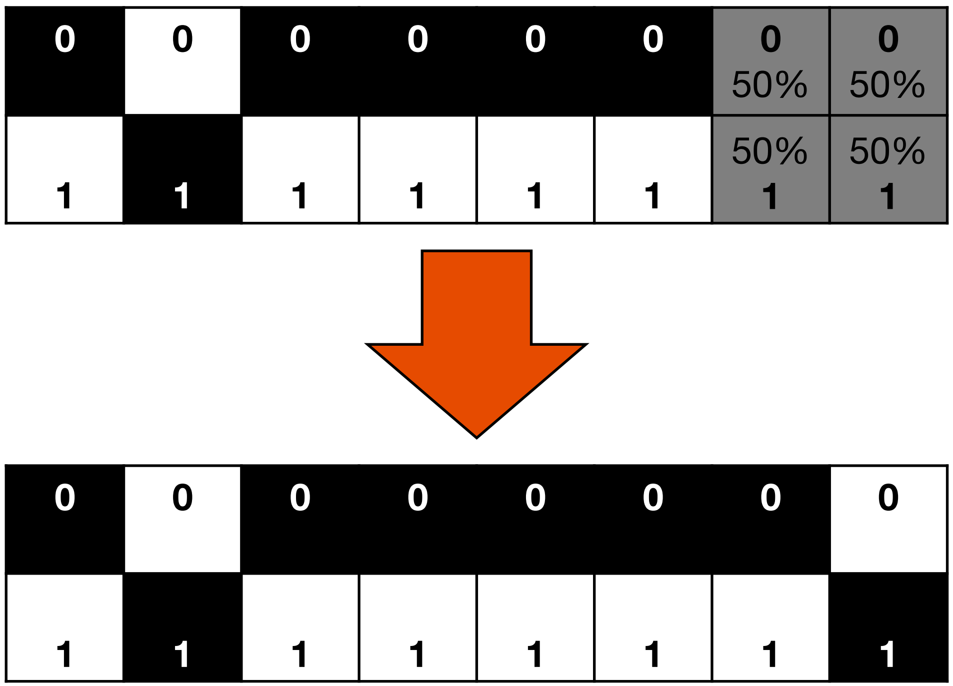
measure single spin

measured spin

changed particles



Entanglement on Registers

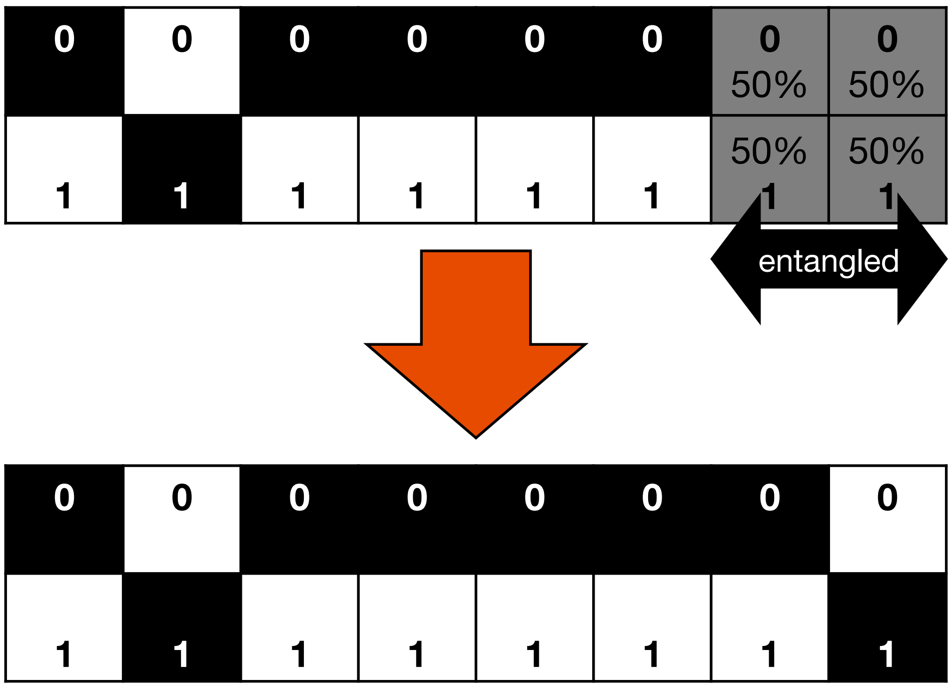


ASCII letters @ A B C at the same time

measuring

ASCII letter A with probability 1/4

Entanglement on Registers

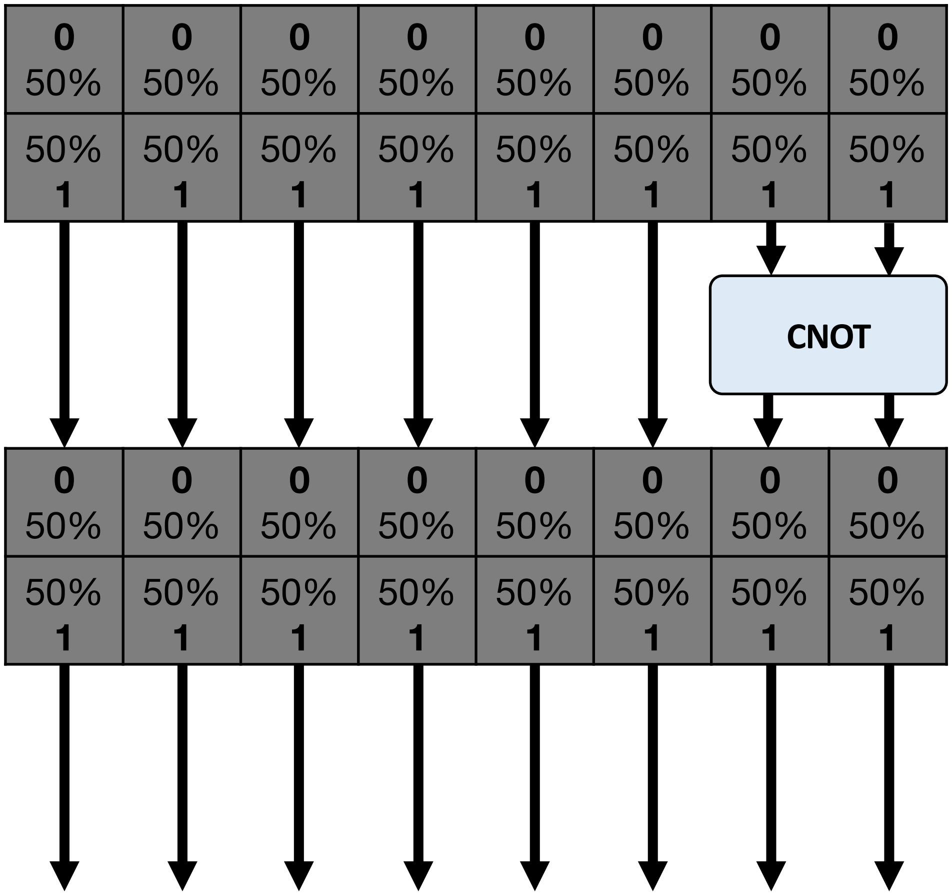


ASCII letters A B at the same time

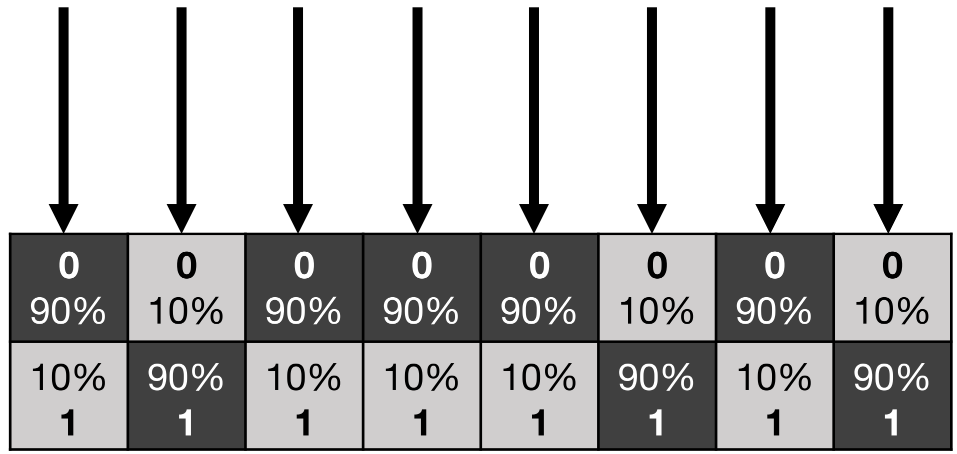
measuring

ASCII letter A with probability 1/2

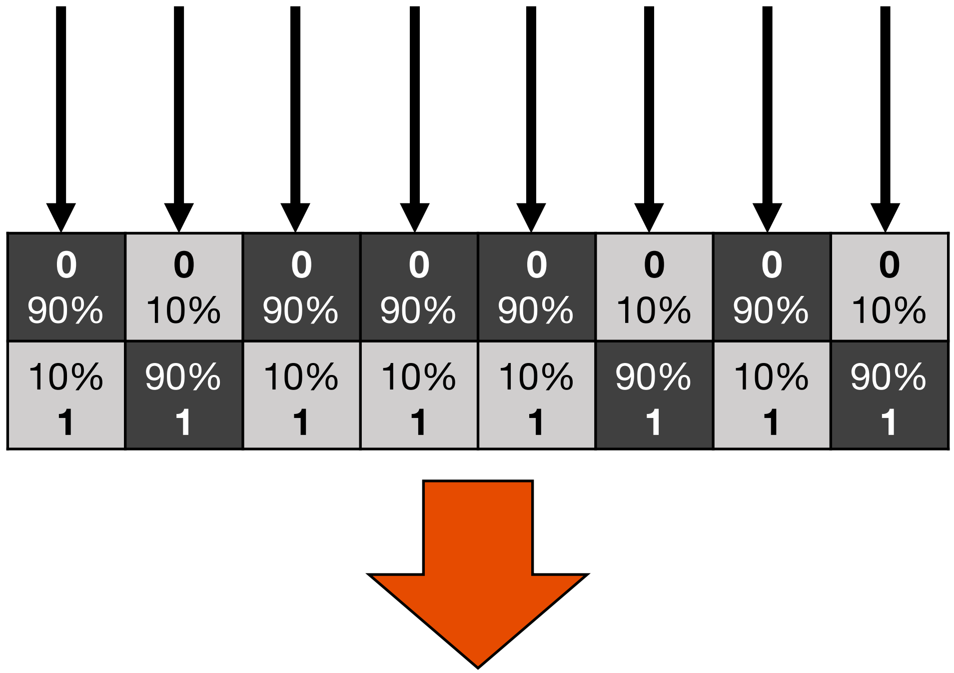
Gate Model



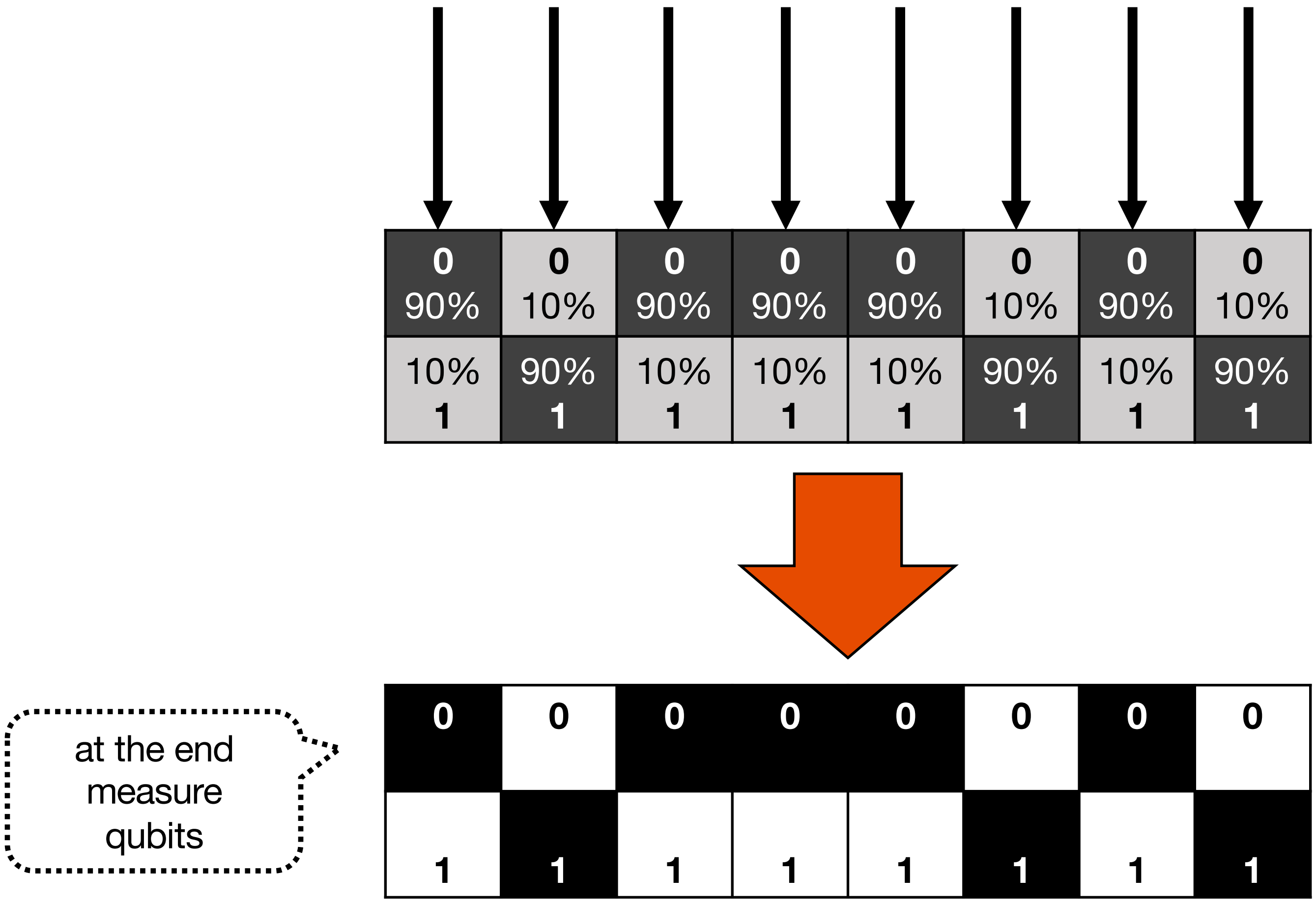
Gate Model



Gate Model



Gate Model

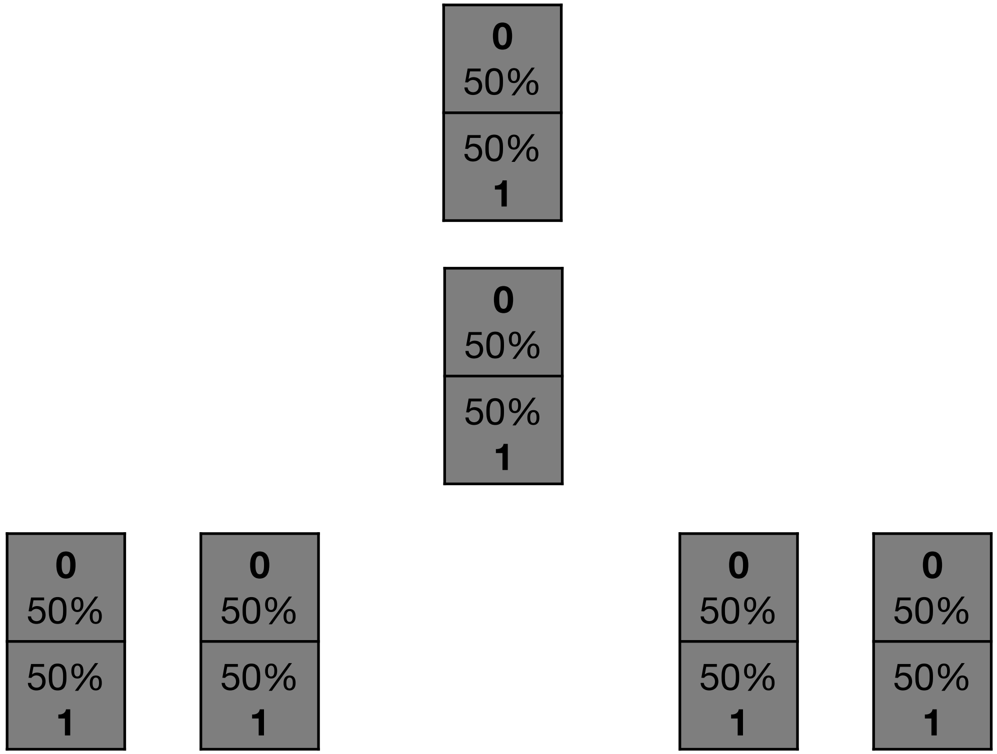


0 0 0 0 0 0 0 0
90% 10% 90% 90% 90% 10% 90% 10%
10% 90% 10% 10% 10% 90% 10% 90%
1 1 1 1 1 1 1 1
at the end measure qubits
0 0 0 0 0 0 0 0
1 1 1 1 1 1 1 1

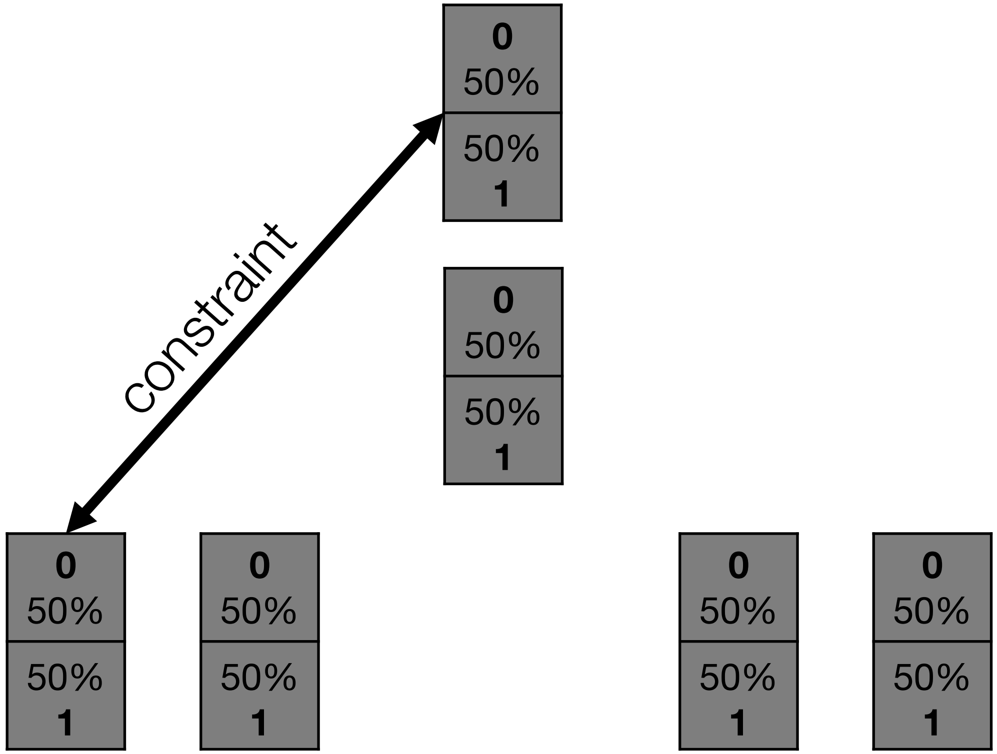
Gate Model

- direct pathway to universal quantum computer
- similar architecture to classical computers
- only protoypes in laboratories
- currently < 100 qubits

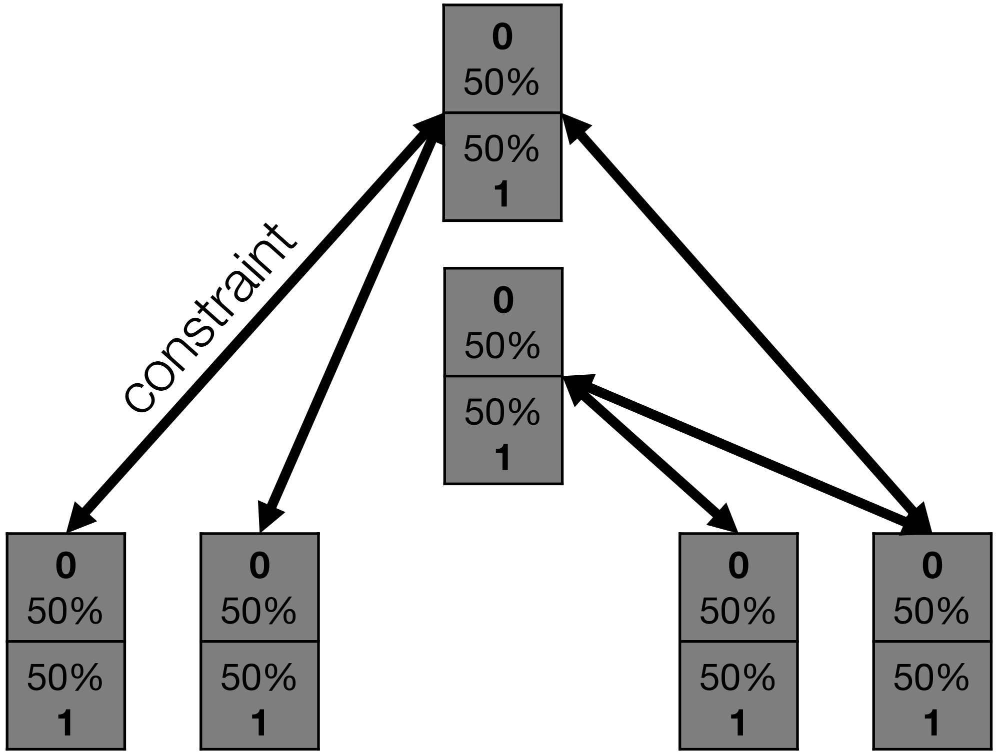
Annealing



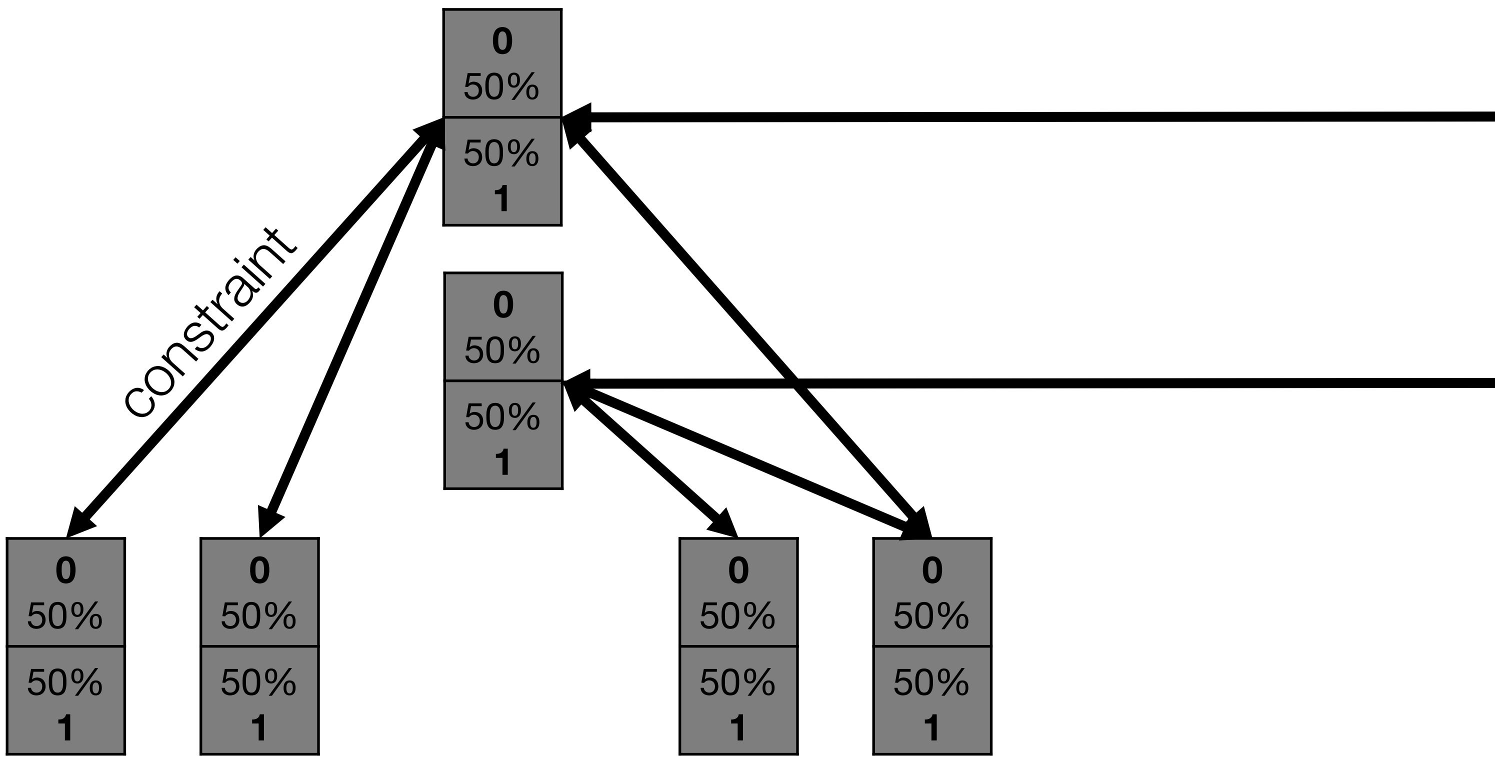
Annealing



Annealing

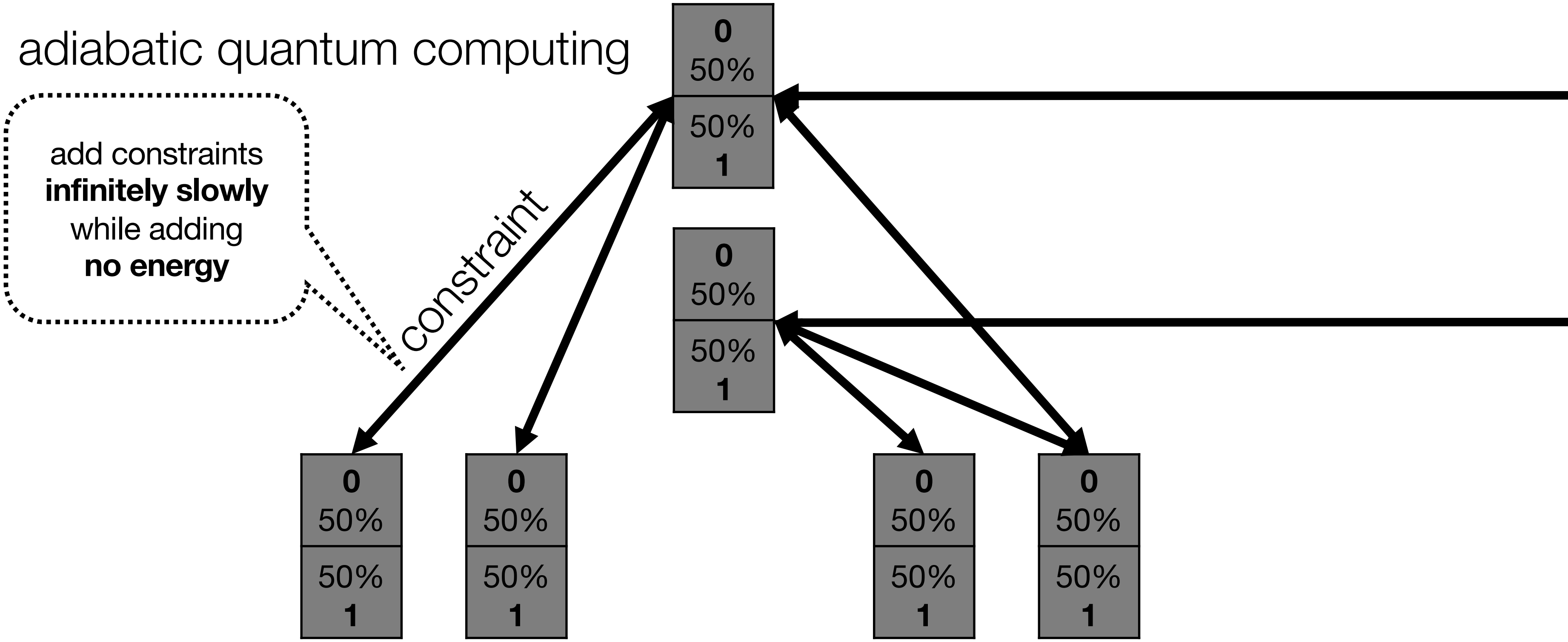


Annealing

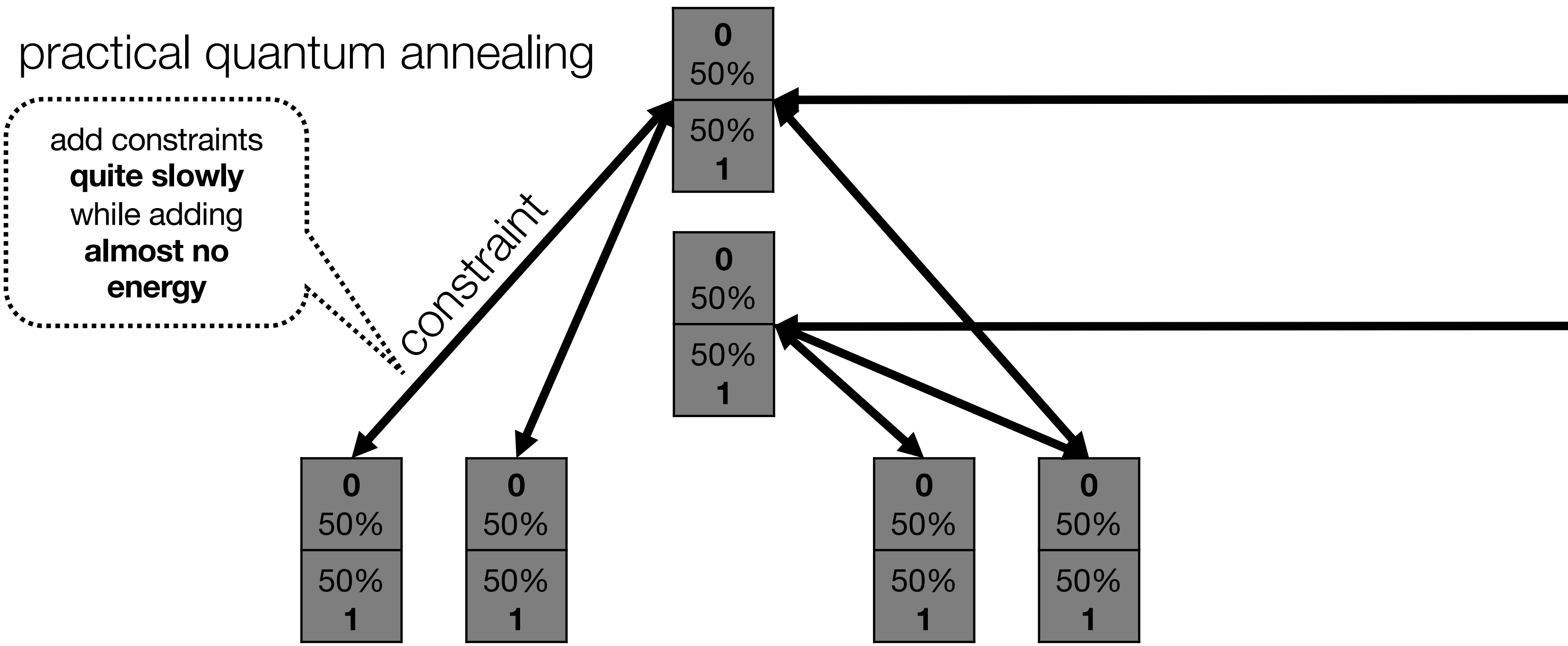


Annealing

adiabatic quantum computing

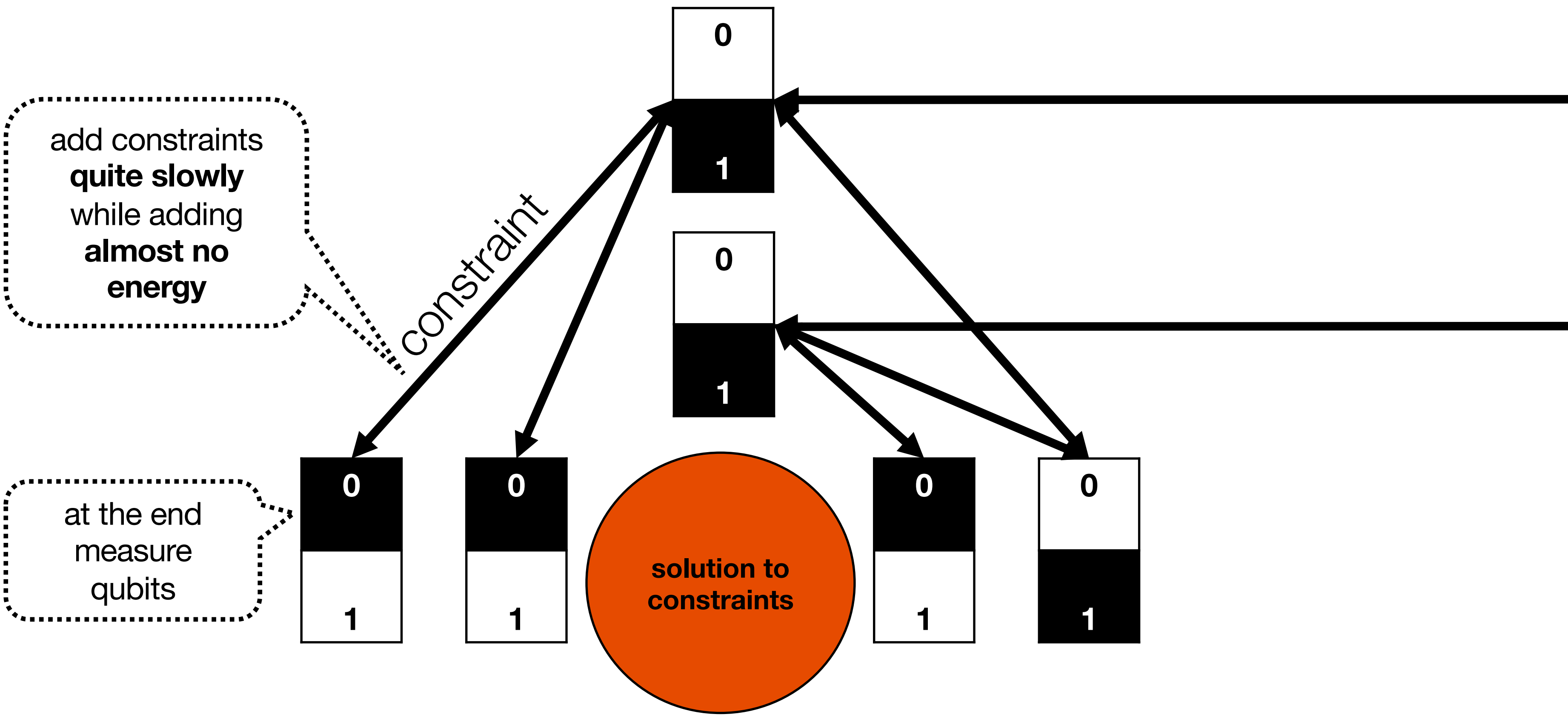


Annealing



practical quantum annealing
add constraints **quite slowly** while adding **almost no energy**
constraint
0
50%
50%
1

Annealing



add constraints **quite slowly** while adding **almost no energy**
constraint
0
1
0
1
at the end measure qubits
0
1
0
1
solution to constraints
0
1
0
1

Annealing

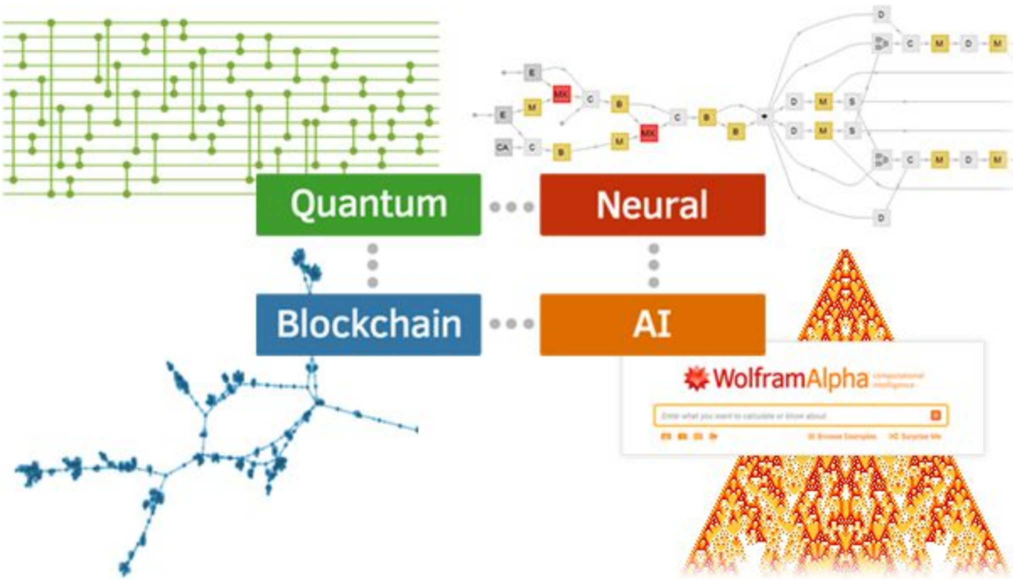
- potentially equally powerful
- architecture built for optimization
- available commercially
- currently > 2000 qubits

D:WAVE
The Quantum Computing Company™

FUJITSU

Bringing it all together…

Quantum Neural Blockchain AI



all these currently relevant *buzzwords* are…

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

Stephen Wolfram. Buzzword Convergence: Making Sense of Quantum Neural Blockchain AI. http://blog.stephenwolfram.com/2018/04/buzzword-convergence-making-sense-of-quantum-neural-blockchain-ai/

Main References

- Thomas Gabor, Andreas Sedlmeier, Marie Kiermeier, Thomy Phan, Marcel Henrich, Monika Picklmair, Berhard Kempter, Cornel Klein, Horst Sauer, Reiner Schmid, and J. Wieghardt. **Scenario Co-Evolution for Reinforcement Learning on a Grid-World Smart Factory Domain.** In *The Genetic and Evolutionary Computation Conference (GECCO)*, 2019.
- Thomas Gabor, Marie Kiermeier, Andreas Sedlmeier, Bernhard Kempter, Cornel Klein, Horst Sauer, Reiner Schmid, and Jan Wieghardt. **Adapting Quality Assurance to Adaptive Systems: The Scenario Coevolution Paradigm.** In *International Symposium on Leveraging Applications of Formal Methods (ISoLA)*, 2018.
- Matthias Homeister. **Quantum Computing verstehen.** Friedr. Vieweg & Sohn Verlag, 2008.

Image Sources

- https://www.bostonmagazine.com/news/2015/07/30/boston-2024-winners-losers
- https://en.wikipedia.org/wiki/The_Thinker#/media/File:Le_Penseur_in_the_Jardin_du_Musée_Rodin,_Paris_14_June_2015.jpg
- https://www.boredpanda.com/jumping-cats/
- https://kinder.wdr.de/tv/wissen-macht-ah/bibliothek/kuriosah/bibliothek-daumen-hoch-100.html
- https://www.medicalnewstoday.com/articles/320289.php#carry_message
- https://en.wikipedia.org/wiki/Mutation#/media/File:Darwin_Hybrid_Tulip_Mutation_2014-05-01.jpg
- https://www.heise.de/ct/artikel/Die-Woche-Microsoft-und-Linux-1283059.html
- https://phys.org/news/2019-10-guillotine-cruel-poisoning.html
- http://blog.stephenwolfram.com/2018/04/buzzword-convergence-making-sense-of-quantum-neural-blockchain-ai/