SEARCH-BASED TEST GENERATION FOR AUTONOMOUS SYSTEMS

Presented by

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Supervisor: Foutse Khomh

POLYTECHNIQUE MONTRÉAL

SEMLA
Trustworthy Engineering of AI Software

AmbieGen

TUTORIAL PLAN

- Introducing autonomous robotic systems testing
- Fuzzing
- Search-based testing
- Building surrogate models
- Hands-on session

WHY TESTING AUTONOMOUS SYSTEMS IS IMPORTANT

Waymo robotaxi accident with San Francisco cyclist draws regulatory review

By **Reuters**

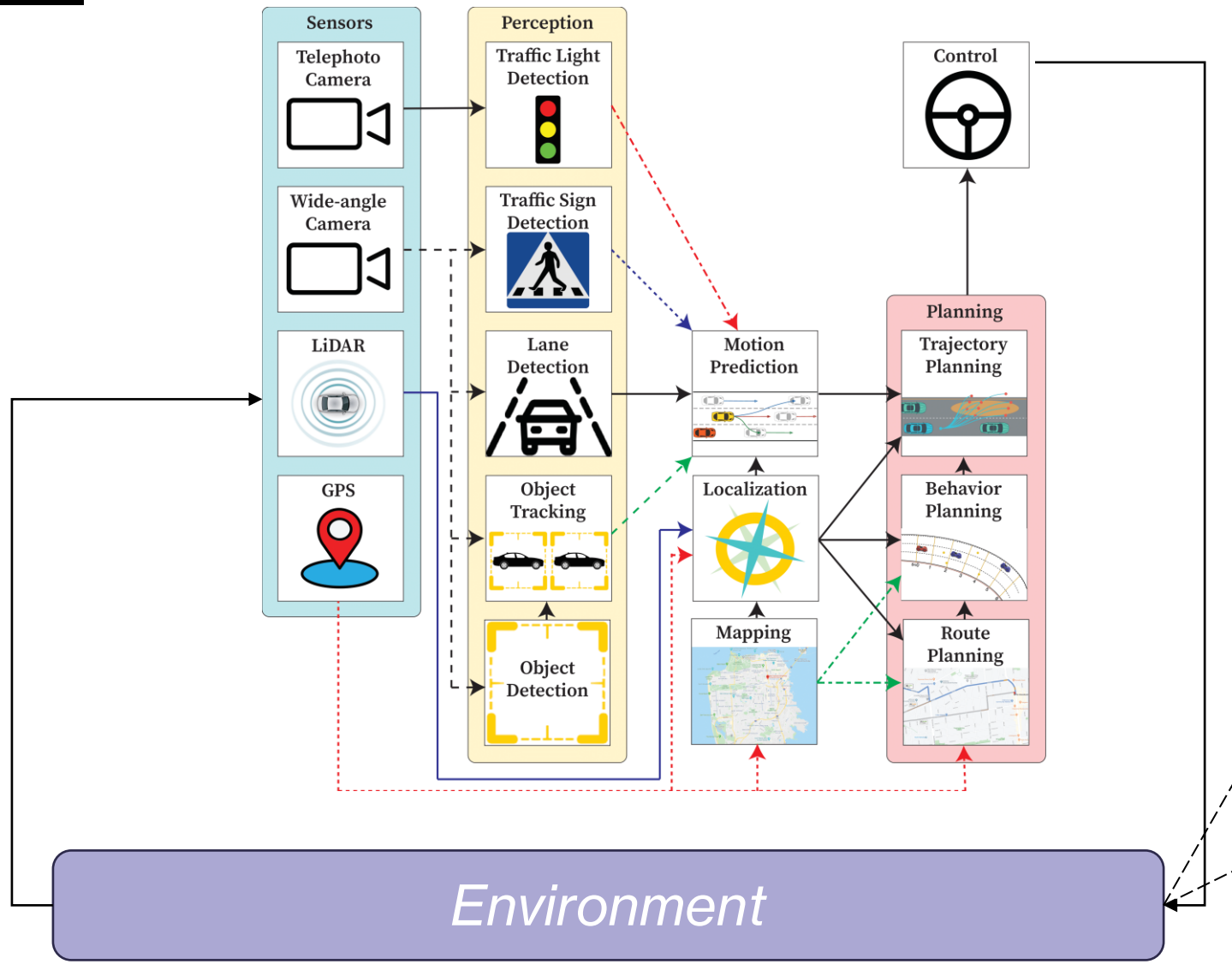
February 8, 2024 3:35 PM EST · Updated a year ago

US agency, California gathering details of accident involving robot taxi and pedestrian

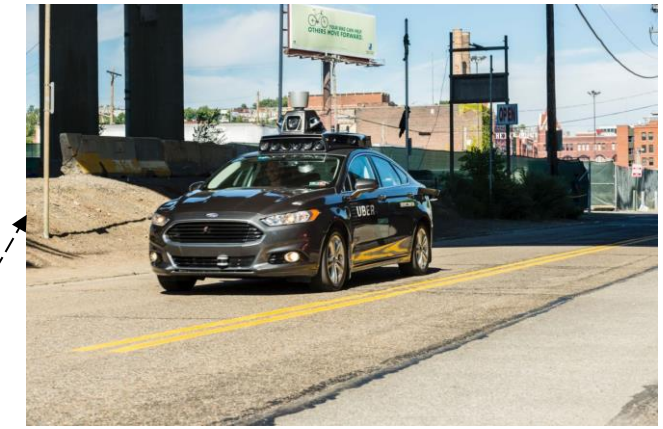
By **David Shepardson**

October 3, 2023 7:56 PM EDT · Updated a year ago

WHY TESTING AUTONOMOUS SYSTEMS IS HARD



Real world



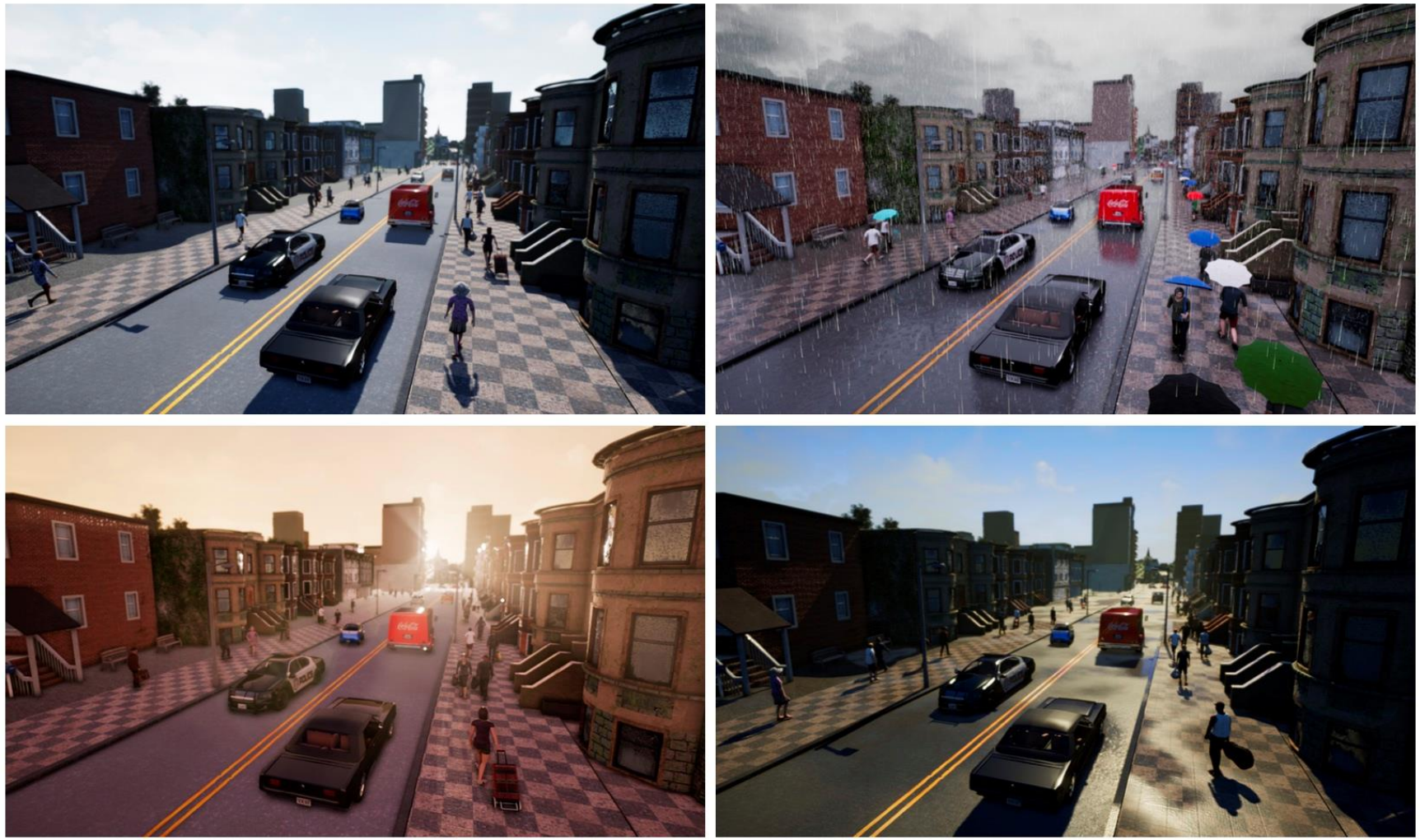
Simulation

Pylot – Pylot 0.2 documentation

SIMULATION PLAYS AN IMPORTANT ROLE IN TESTING

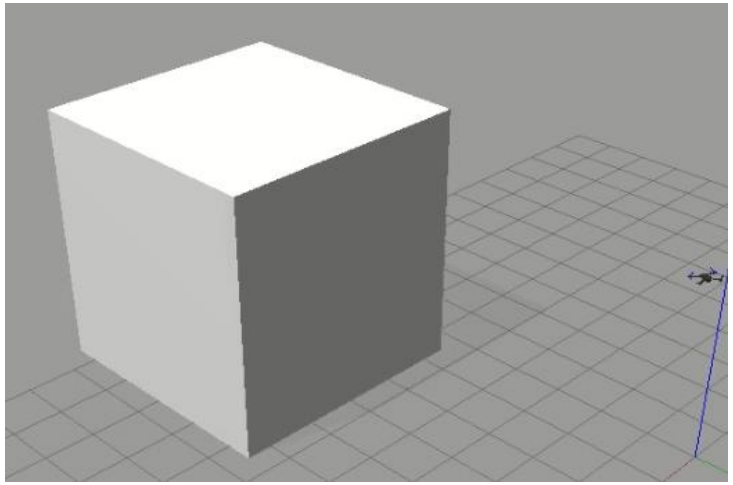
PARAMETER SEARCH SPACE IS HUGE…

CARLA: An Open Urban Driving Simulator - Vladlen Koltun

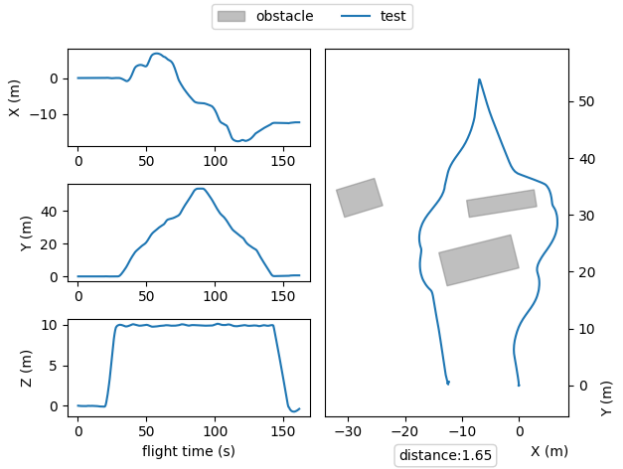


RUNNING EXAMPLE

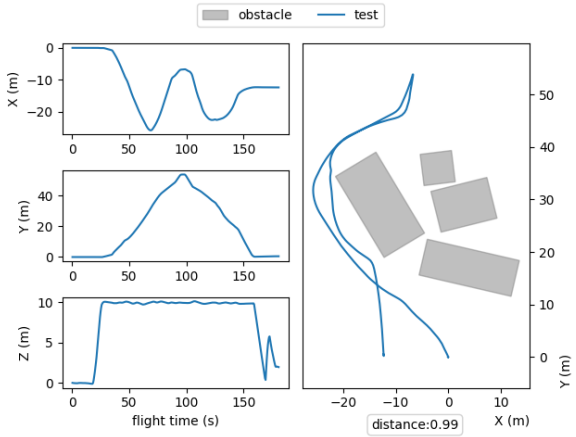
- 1 objective
- 3 constraints
- 19 dimensions
- ~120 s per evaluation



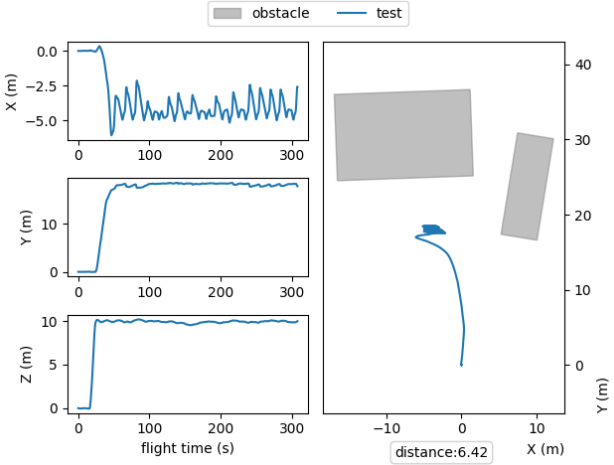
Valid test case



Failed test case



Invalid test case



SEARCH-BASED TESTING TECHNIQUES

FUZZING

FUZZING: RANDOM BUT USEFUL

UNIX Utility Programs

Program	Typical use
cat	Concatenate multiple files to standard output
chmod	Change file protection mode
cp	Copy one or more files
cut	Cut columns of text from a file
grep	Search a file for some pattern
head	Extract the first lines of a file
ls	List directory
make	Compile files to build a binary
mkdir	Make a directory
od	Octal dump a file
paste	Paste columns of text into a file
pr	Format a file for printing
rm	Remove one or more files
rmdir	Remove a directory
sort	Sort a file of lines alphabetically
tail	Extract the last lines of a file
tr	Translate between character sets

"9[=~`|zZ3P]\n"

"\x10\x11\x12Test\n"

"Data\x00Split\x00Here\n"

"\x00Hi\x1bThere\x7f\n"

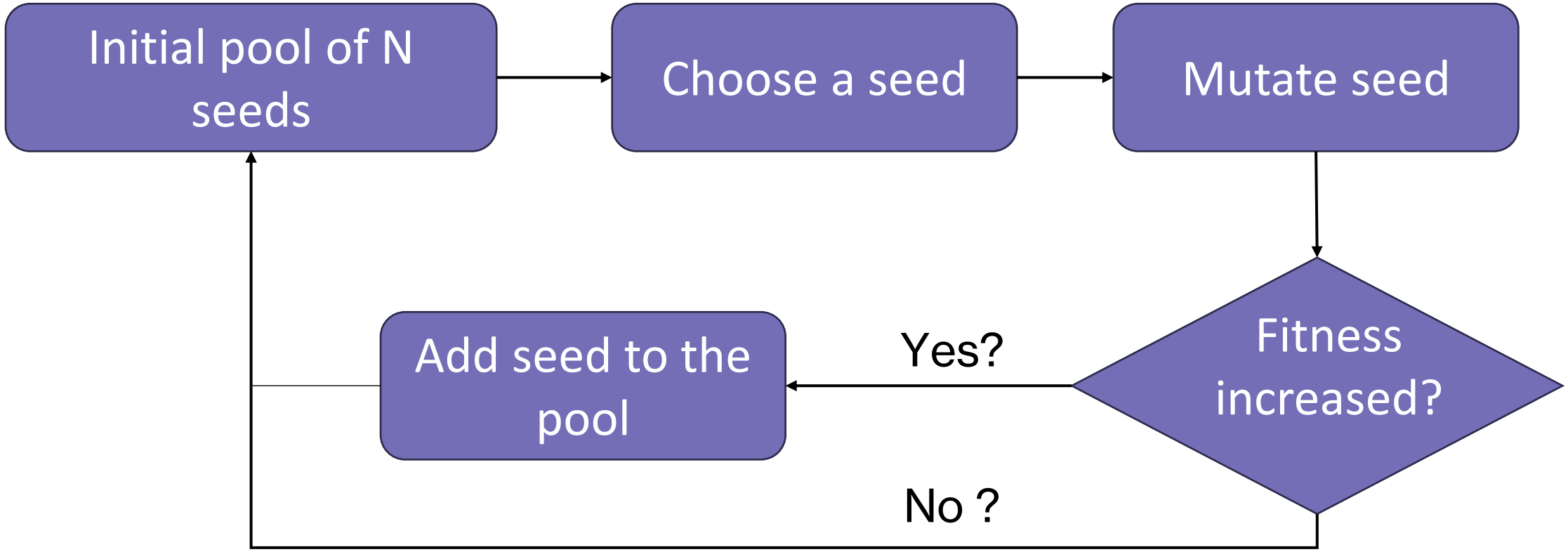
MUTATION-BASED FUZZING

seed_input = "Welcome to SEMLA 2025"

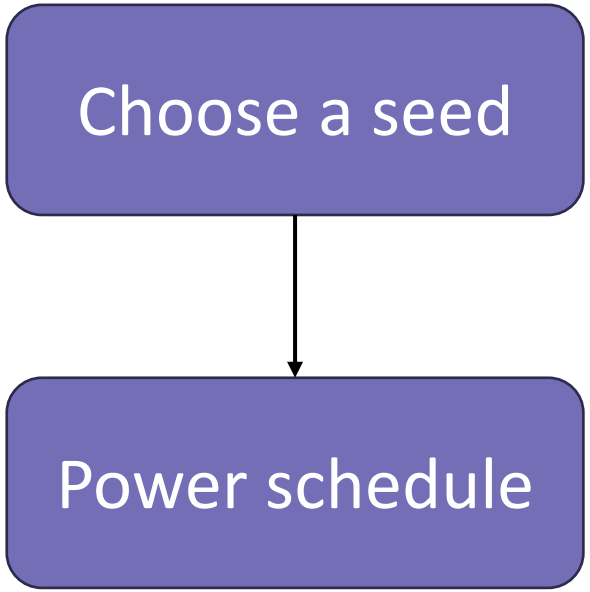
'Welcoxe to SEMLA 2025'
'Welcome to SEMLa 2025'
'Wblcome to SEMLA 2025'
'Welcome to SEMLA<2025'
'Welcome to SEMLA 2*25'
'Welcome to S@MLA 2025'
'Welcome to SEMLA 20Z5'
'Welcome to SEMLA 2&25'
'Welcome to S!MLA 2025'
'Welcome to SEMLA 202q'

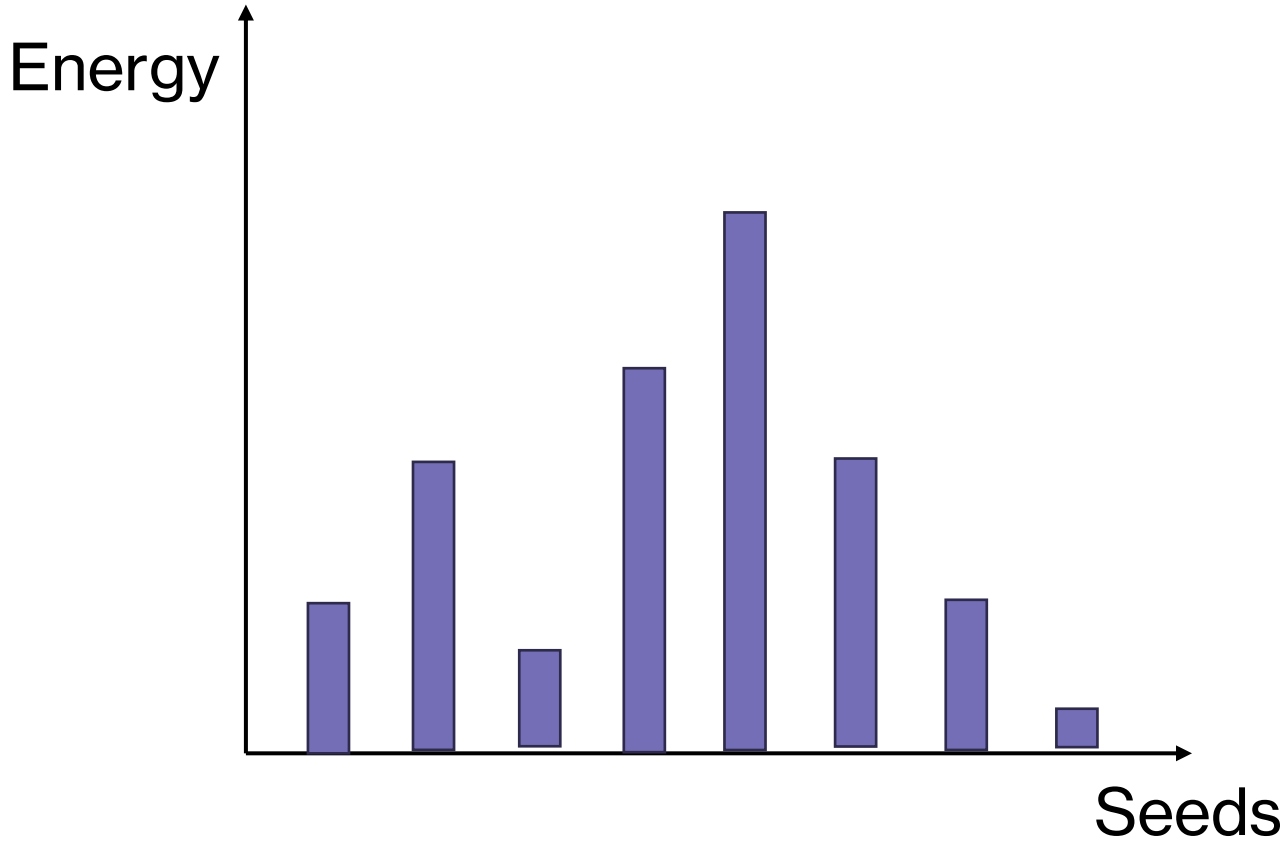
SMARTER FUZZING WITH FEEDBACK

SMARTER FUZZING WITH FEEDBACK



CHOOSING SEED SMARTLY WITH POWER SCHEDULES



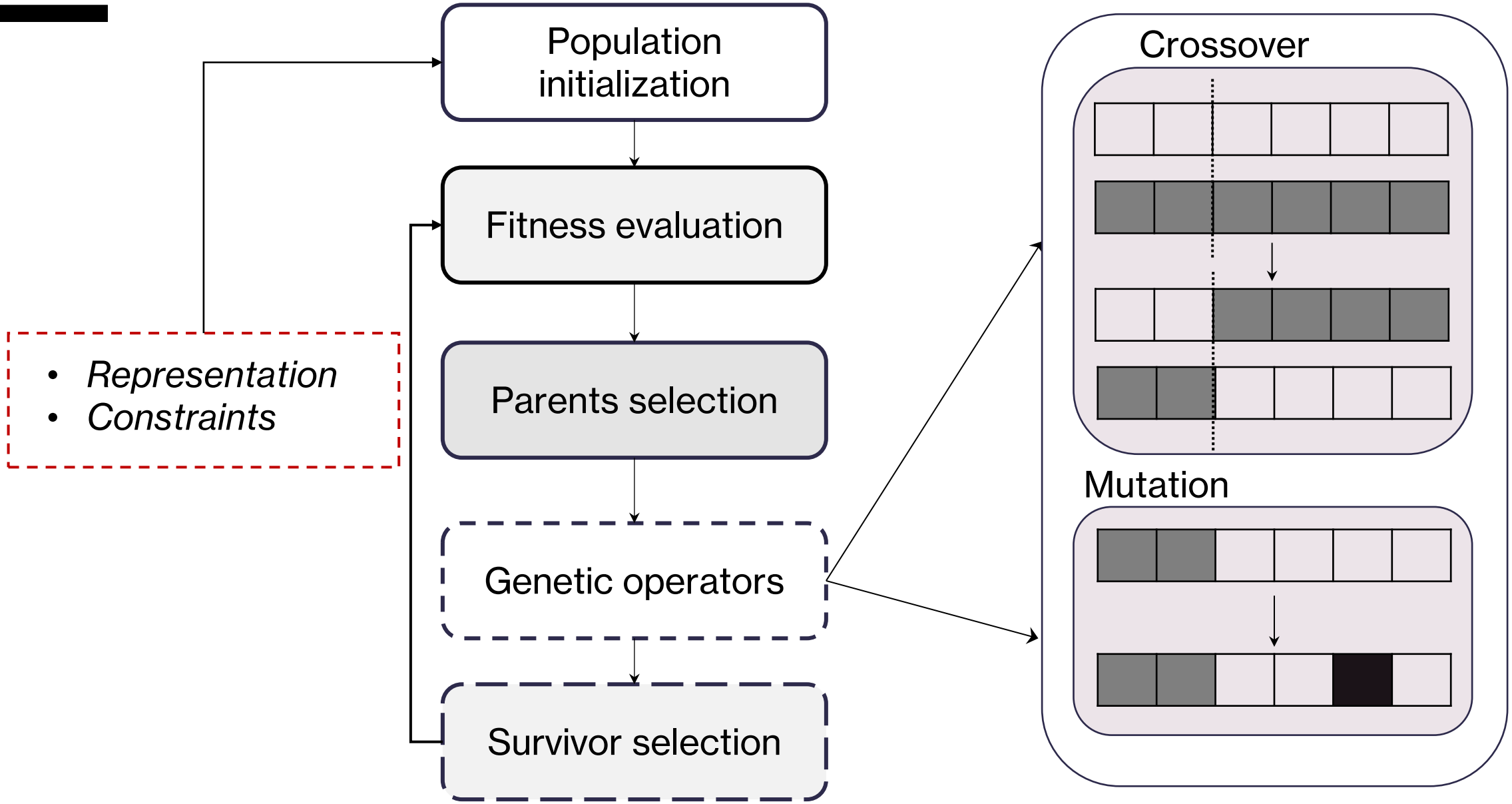


FUZZING LIMITATIONS

- Performance strongly depends on the input seeds
- Local search oriented
- Not handling multiple objective natively
- Works best when evaluations are fast

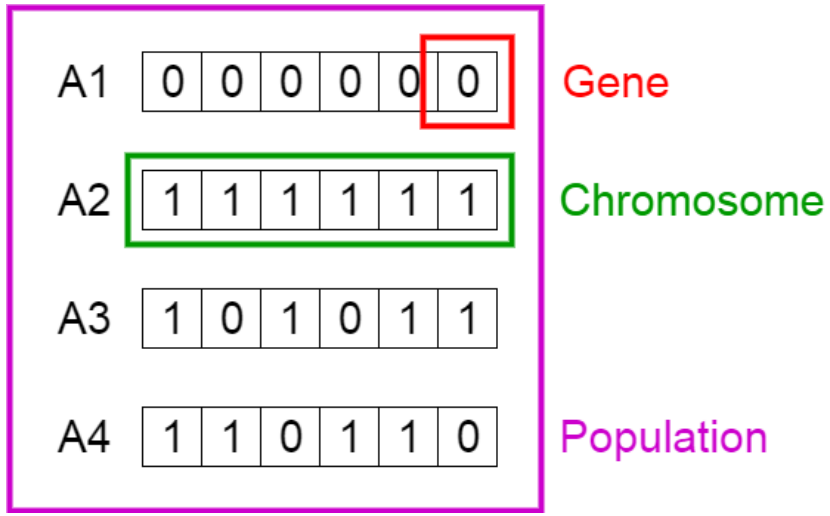
EVOLUTIONARY SEARCH

EVOLUTIONARY ALGORITHMS: NATURE-INSPIRED TESTING



REPRESENTATION

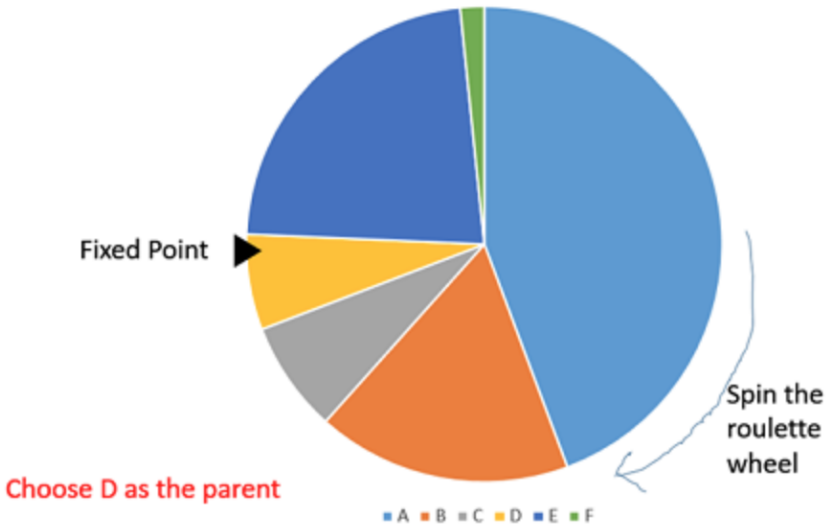
phenotype: object in original problem context, the outside
genotype: code to denote that object, the inside (chromosome, "digital DNA")



- Binary
- Integer
- Real-valued
- Permutation
- Custom

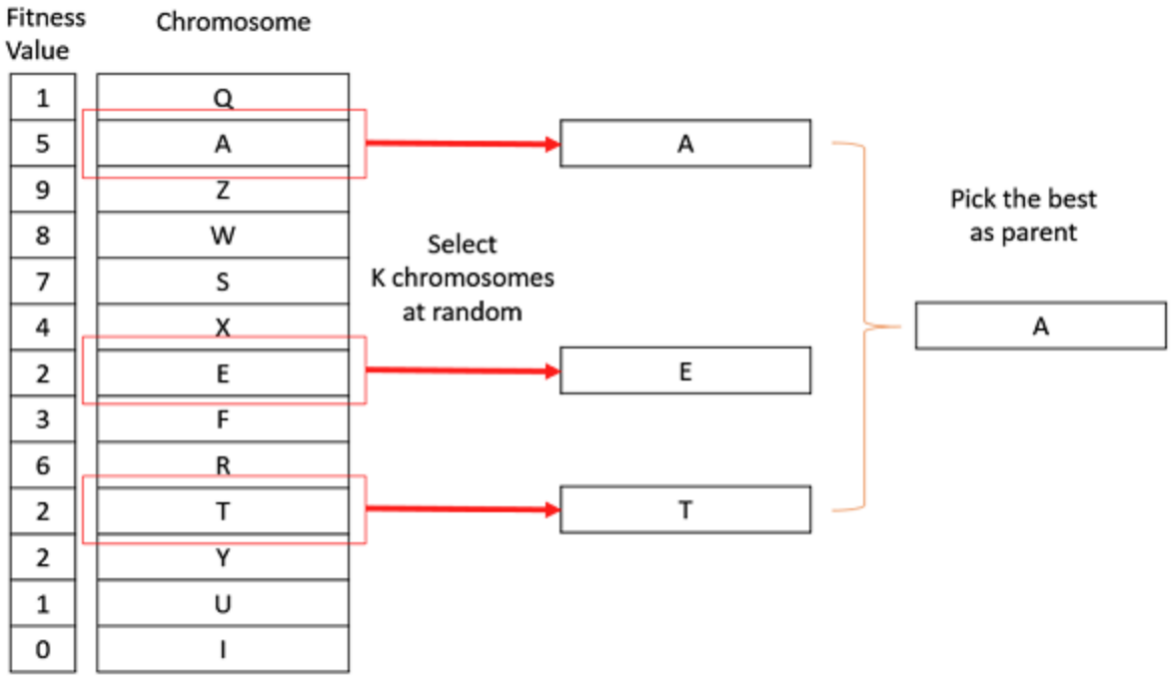
PARENTS SELECTION

Roulette Wheel Selection



Chromosome	Fitness Value
A	8.2
B	3.2
C	1.4
D	1.2
E	4.2
F	0.3

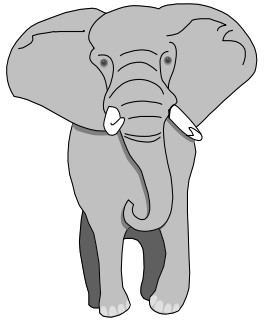
Tournament Selection



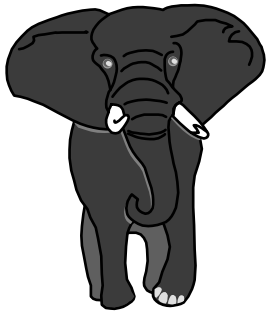
MUTATIONS

Binary representation

before 1 1 1 1 1 1 1



after 1 1 1 0 1 1 1



MUTATIONS

Integer representation

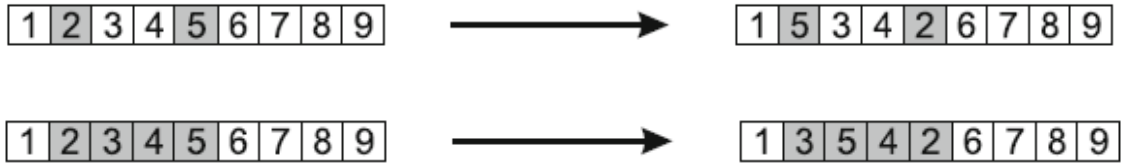
- Random Resetting
- Creep Mutation

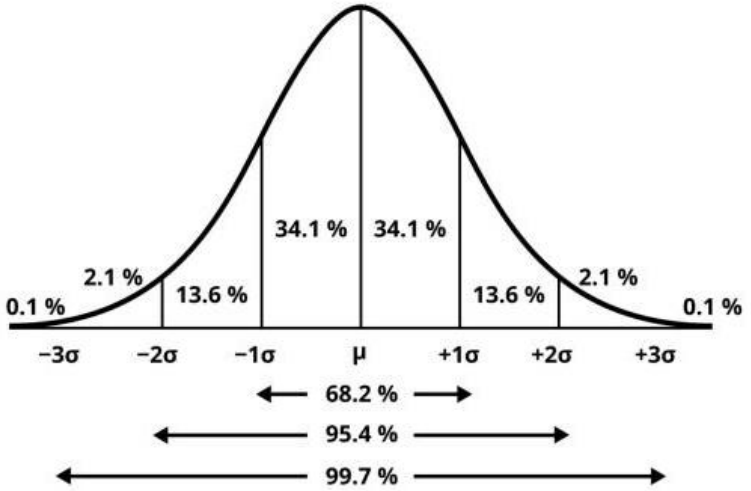
Real-value representation

- Uniform Mutation
- Nonuniform Mutation

σ – mutation step size

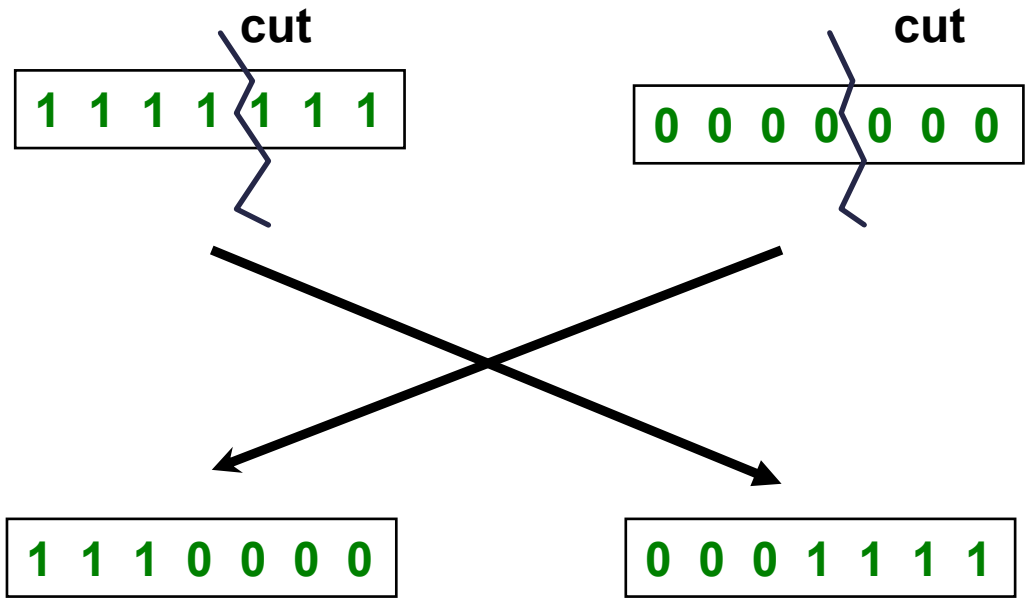
Permutation representation

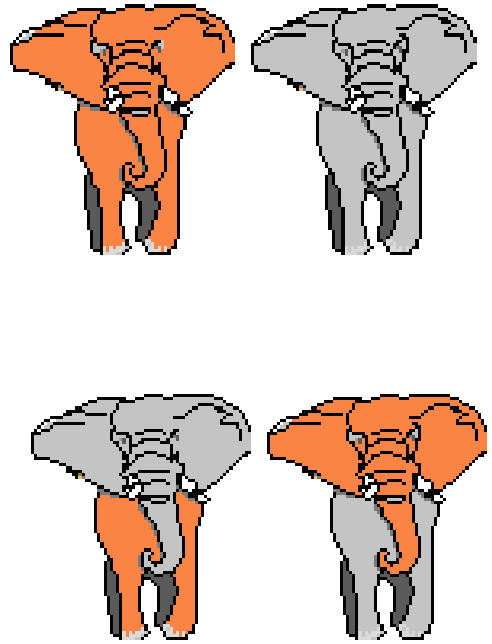




CROSSOVER

Parents

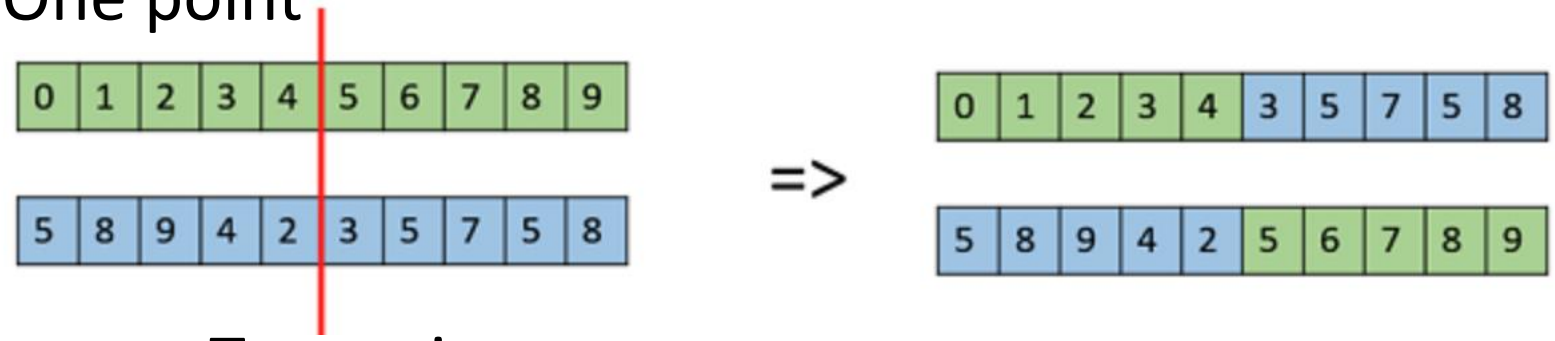




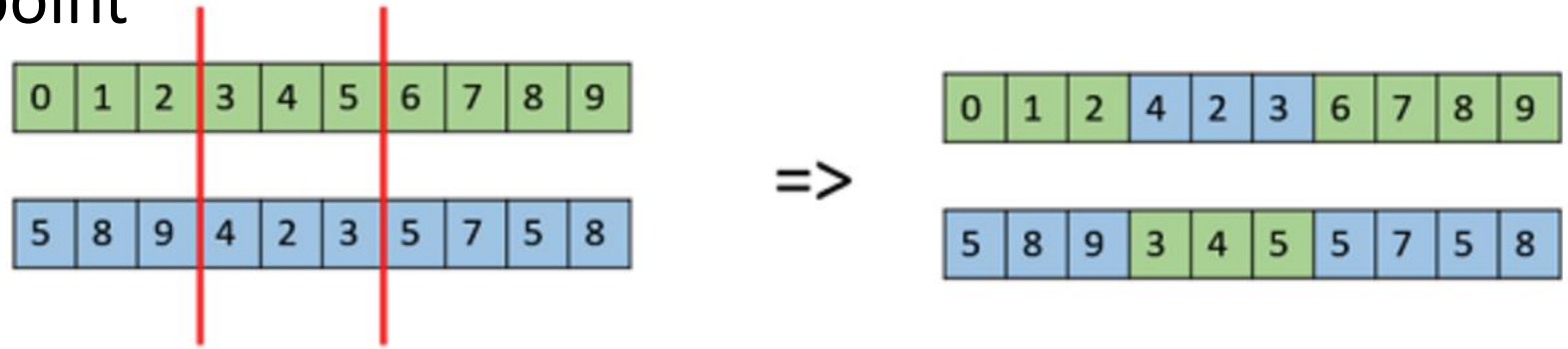
Offspring

CROSSOVER

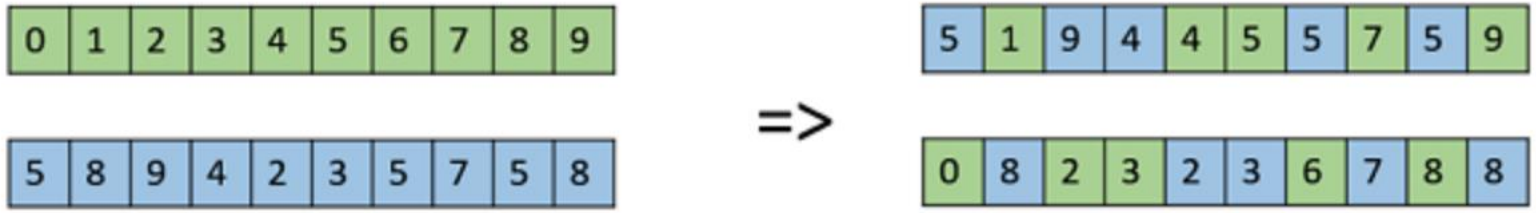
One point



Two point

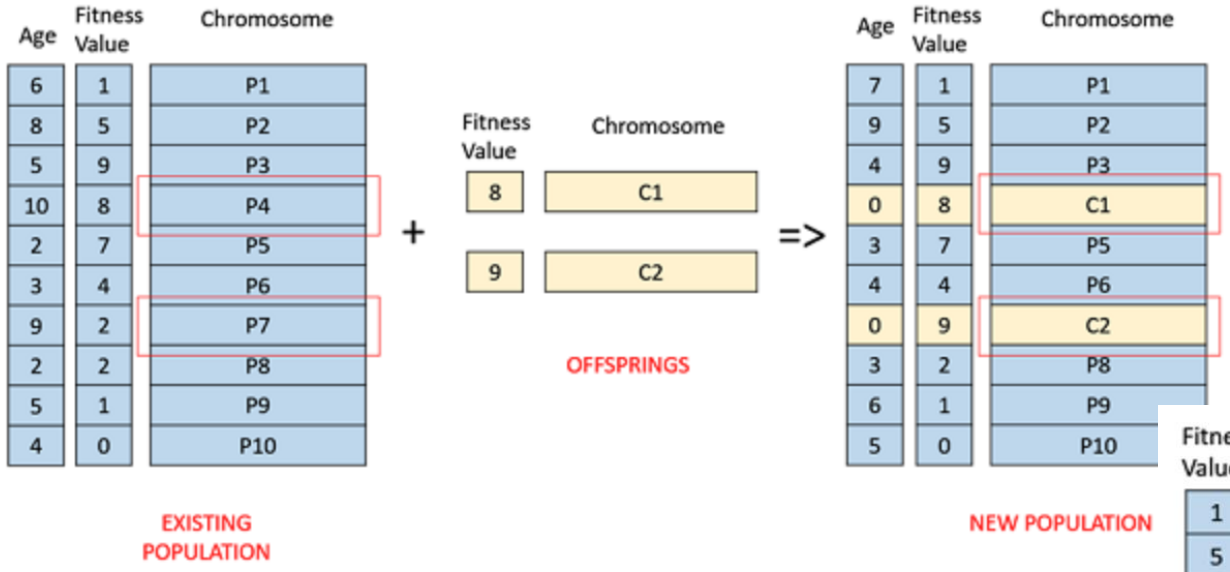


Uniform

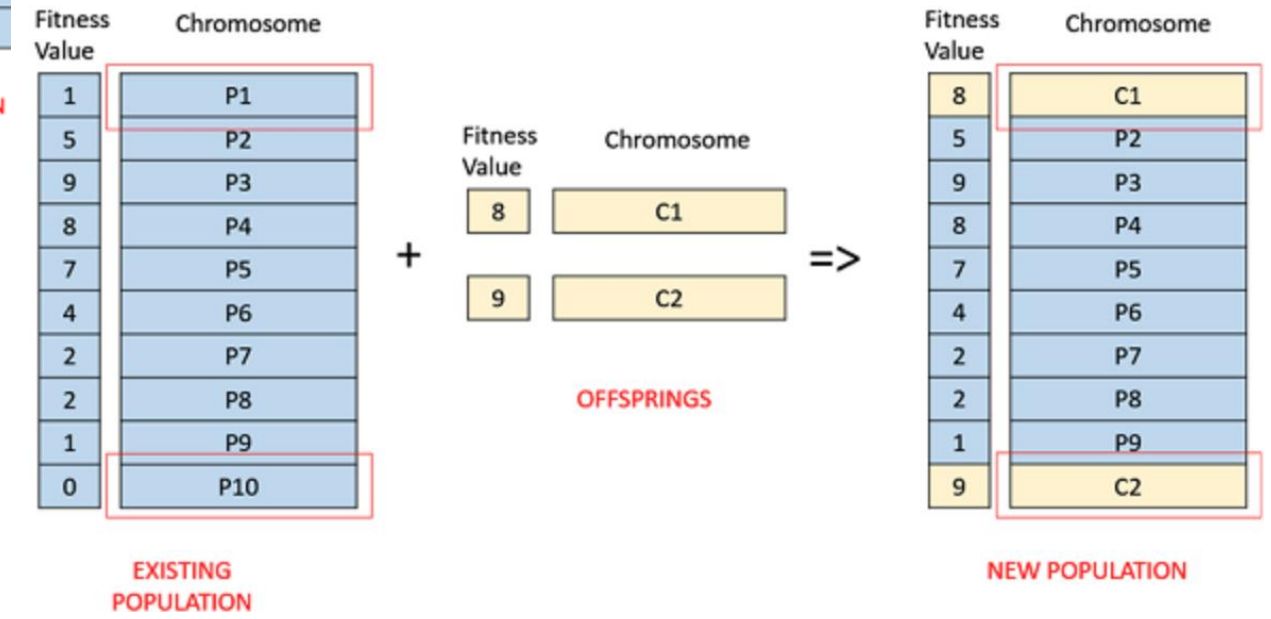


SURVIVOR SELECTION

Age based

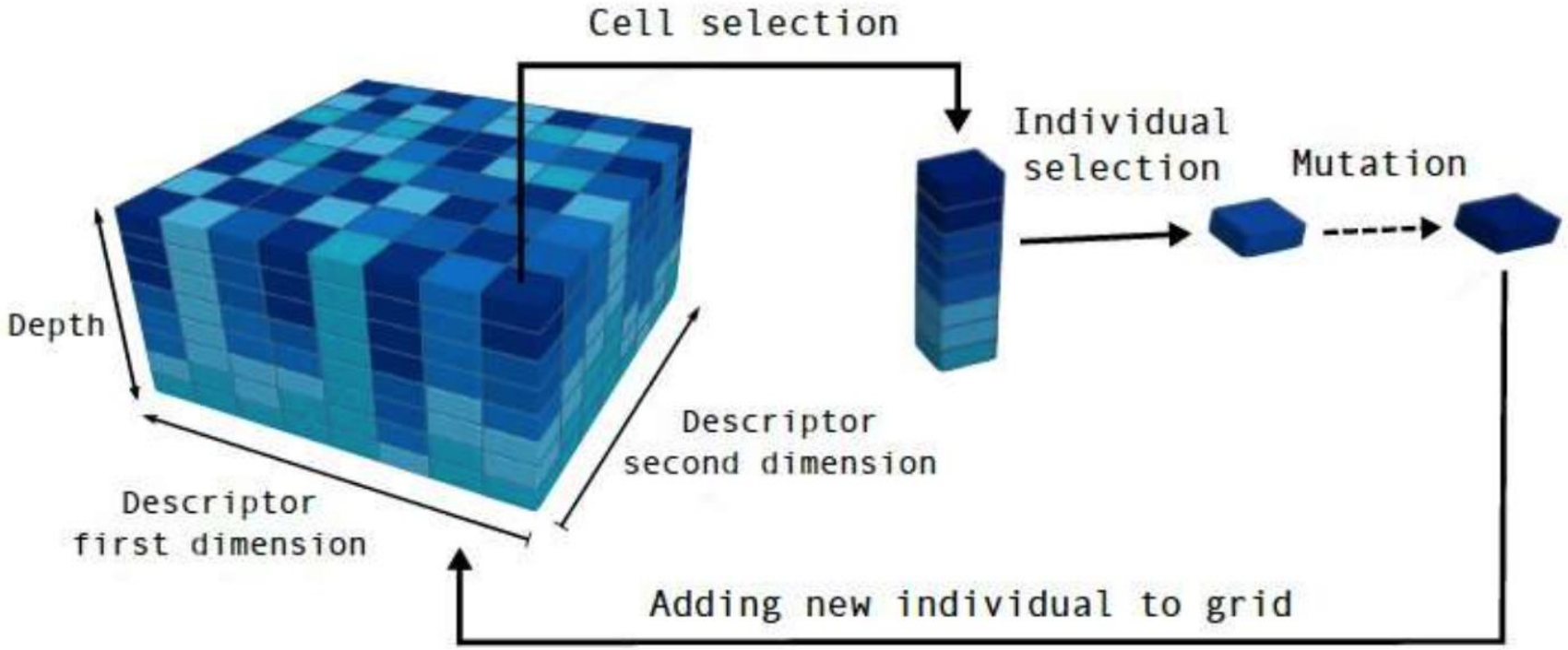


Fitness based



MAINTAINING DIVERSITY

- Removing duplicates based on distance metrics
- Quality-diversity search



RESEARCH EXAMPLES

Automatically Testing Self-Driving Cars with Search-Based Procedural Content Generation

Alessio Gambi
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Marc Mueller
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BeamNG GmbH
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Gordon Fraser
gordon.fraser@uni-passau.de
University of Passau
Passau, Germany

AV-Fuzzer: Finding Safety Violations in Autonomous Driving Systems

Guanpeng Li*, Yiran Li*, Saurabh Jha*, Timothy Tsai†, Michael Sullivan†, Siva Kumar Sastry Hari†, Zbigniew Kalbarczyk*, Ravishankar Iyer*

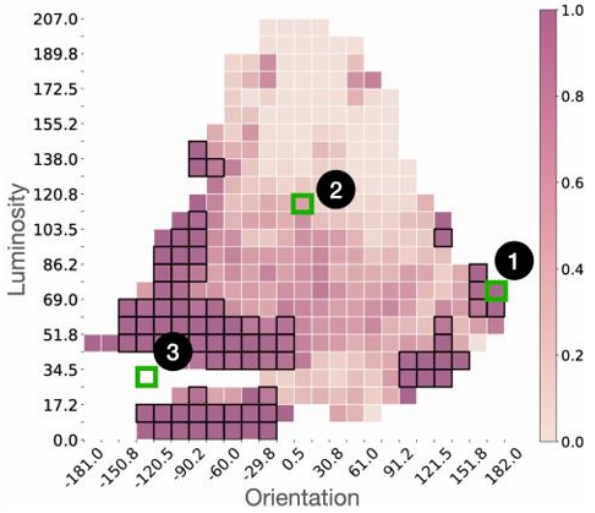
*University of Illinois at Urbana-Champaign, †NVIDIA

RESEARCH EXAMPLES

DeepAtash: Focused Test Generation for Deep Learning Systems

Authors: Tahereh Zohdinasab, Vincenzo Riccio, Paolo Tonella | Authors Info & Claims

ISSTA 2023: Proceedings of the 32nd ACM SIGSOFT International Symposium on Software Testing and Analysis
Pages 954 - 966 • https://doi.org/10.1145/3597926.3598109

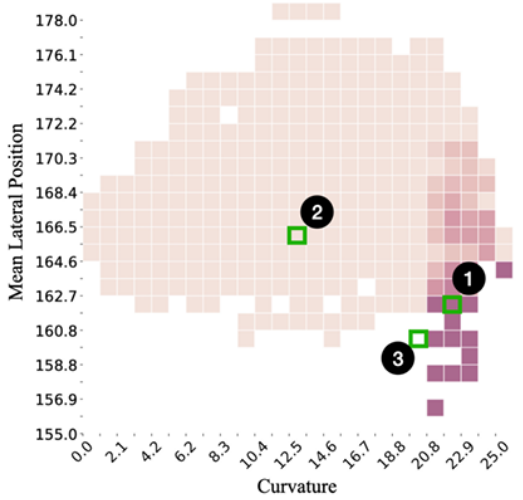


Focused Test Generation for Autonomous Driving Systems

Authors: Tahereh Zohdinasab, Vincenzo Riccio, Paolo Tonella | Authors Info & Claims

ACM Transactions on Software Engineering and Methodology, Volume 33, Issue 6 • Article No.: 152, Pages 1 - 32
https://doi.org/10.1145/3664605

Published: 27 June 2024 Publication History



RESEARCH EXAMPLES

Information and Software Technology
Volume 149, September 2022, 106936

A search-based framework for automatic generation of testing environments for cyber–physical systems

Dmytro Humeniuk, Foutse Khomh, Giuliano Antoniol

Reinforcement Learning Informed Evolutionary Search for Autonomous Systems Testing

Authors: Dmytro Humeniuk, Foutse Khomh, Giuliano Antoniol | Authors Info & Claims

ACM Transactions on Software Engineering and Methodology, Volume 33, Issue 8 • Article No.: 216, Pages 1 - 45
https://doi.org/10.1145/3680468

In-Simulation Testing of Deep Learning Vision Models in Autonomous Robotic Manipulators

Authors: Dmytro Humeniuk, Houssem Ben Braiek, Thomas Reid, Foutse Khomh | Authors Info & Claims

ASE '24: Proceedings of the 39th IEEE/ACM International Conference on Automated Software Engineering
Pages 2187 - 2198 • https://doi.org/10.1145/3691620.3695281

Representation Improvement in Latent Space for Search-Based Testing of Autonomous Robotic Systems

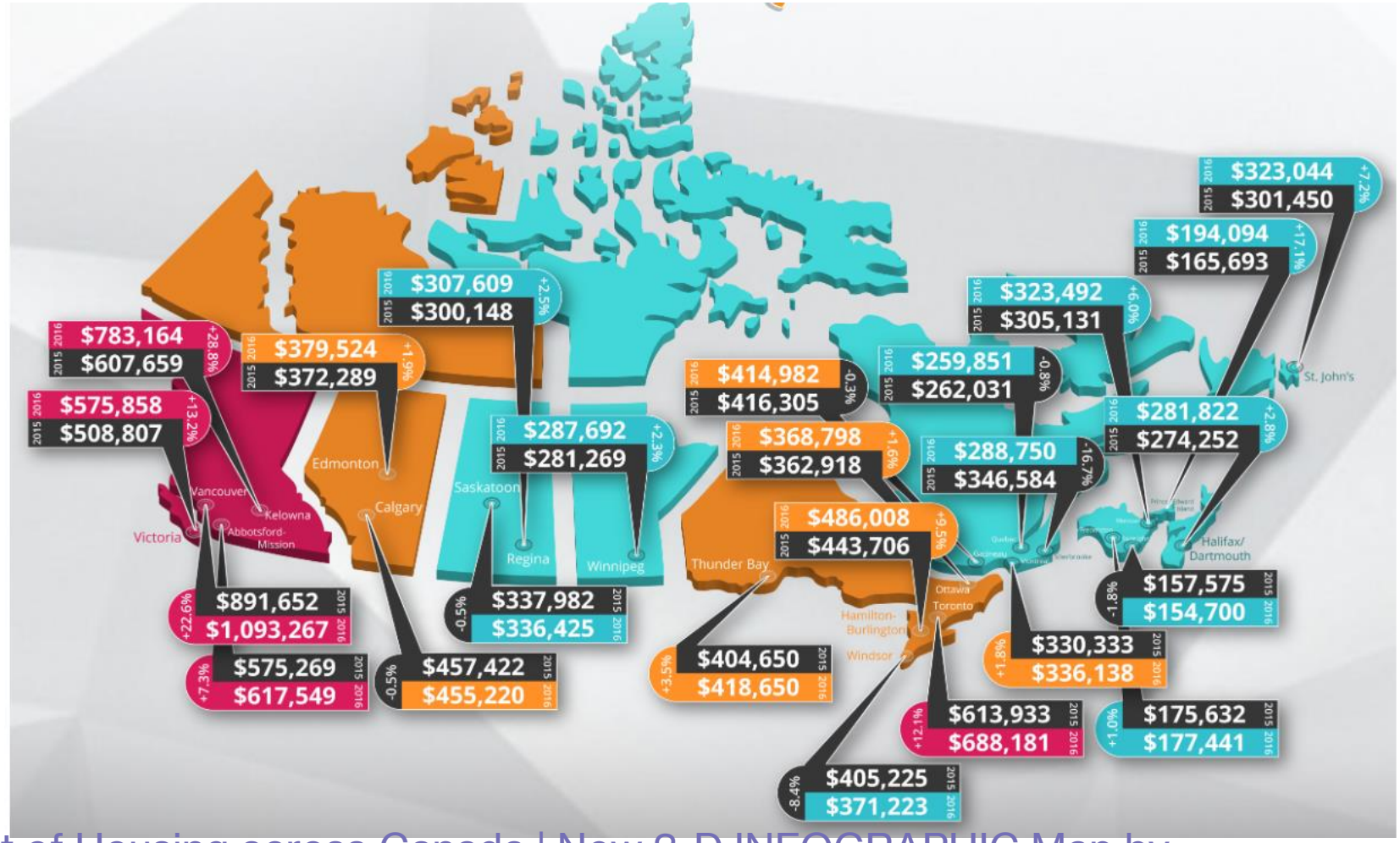
Dmytro Humeniuk, Foutse Khomh

EVOLUTIONARY LIMITATIONS

- Sampling inefficiency
- No explicit learning component (gradient-free)

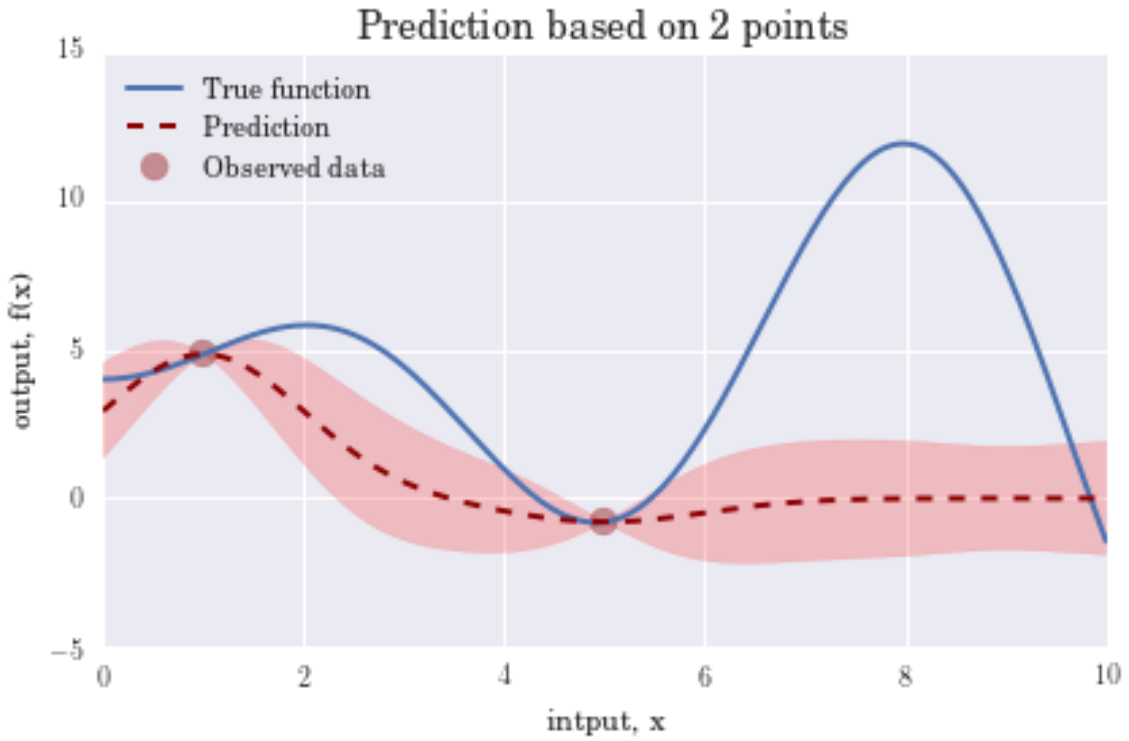
BAYESIAN OPTIMIZATION

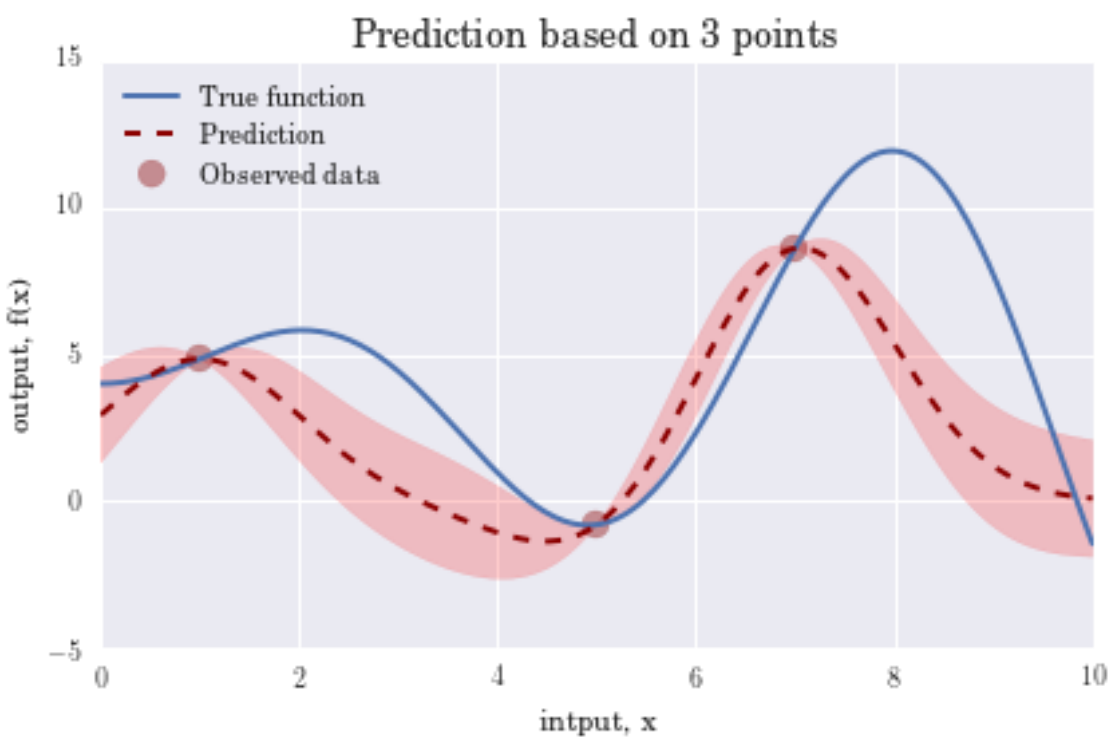
BUYING A HOUSE



[National Average Cost of Housing across Canada | New 3-D INFOGRAPHIC Map by RentSeeker.ca - RentSeeker Blog]

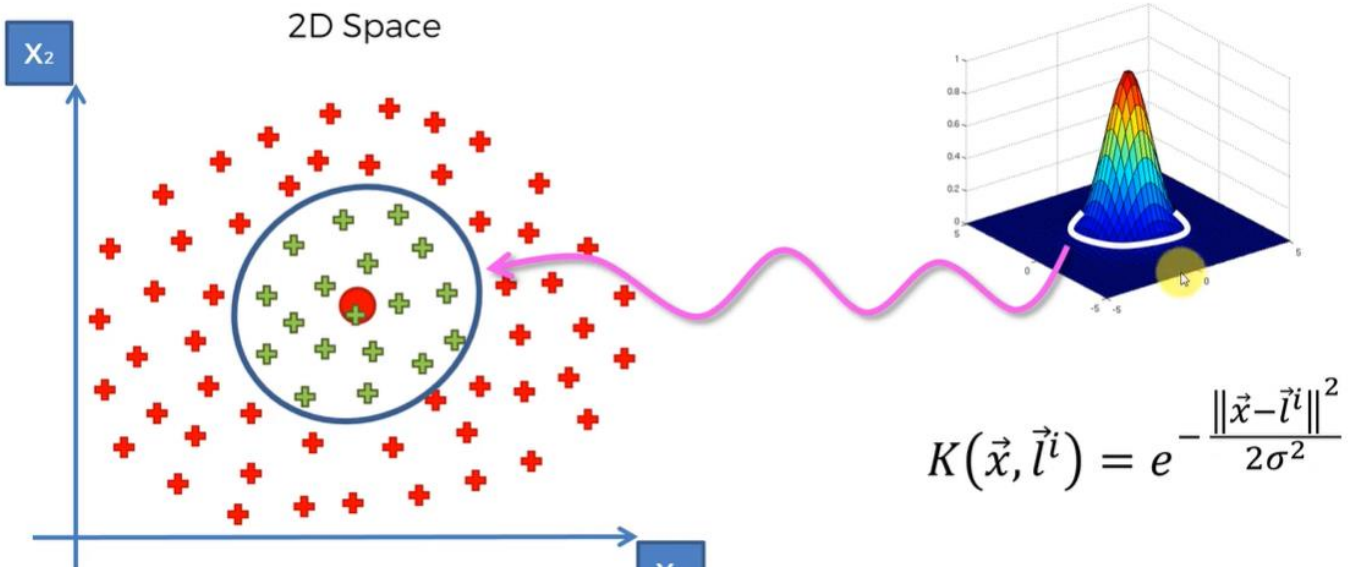
FITTING A GAUSSIAN PROCESS TO A DATASET





SIMILARITY IS ESTIMATED BASED ON KERNELS

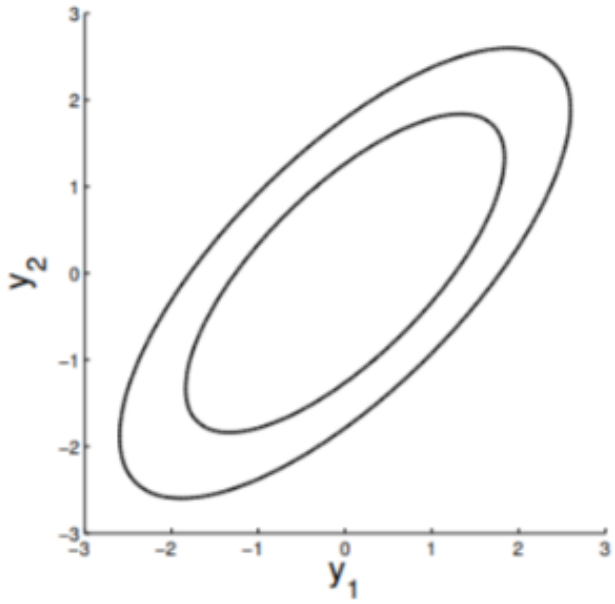
Radial basis function



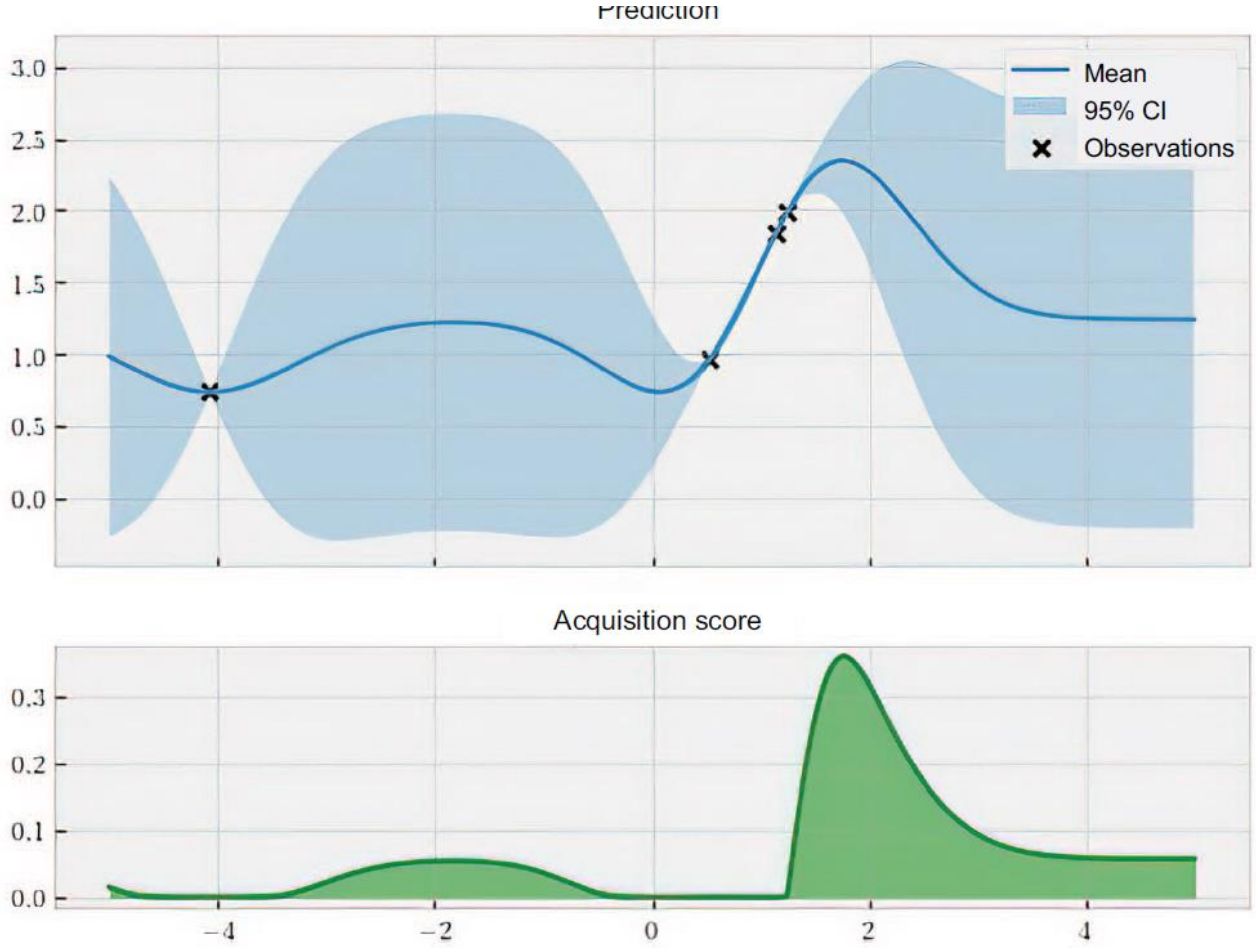
$$K(\vec{x}, \vec{l}^i) = e^{-\frac{\|\vec{x}-\vec{l}^i\|^2}{2\sigma^2}}$$

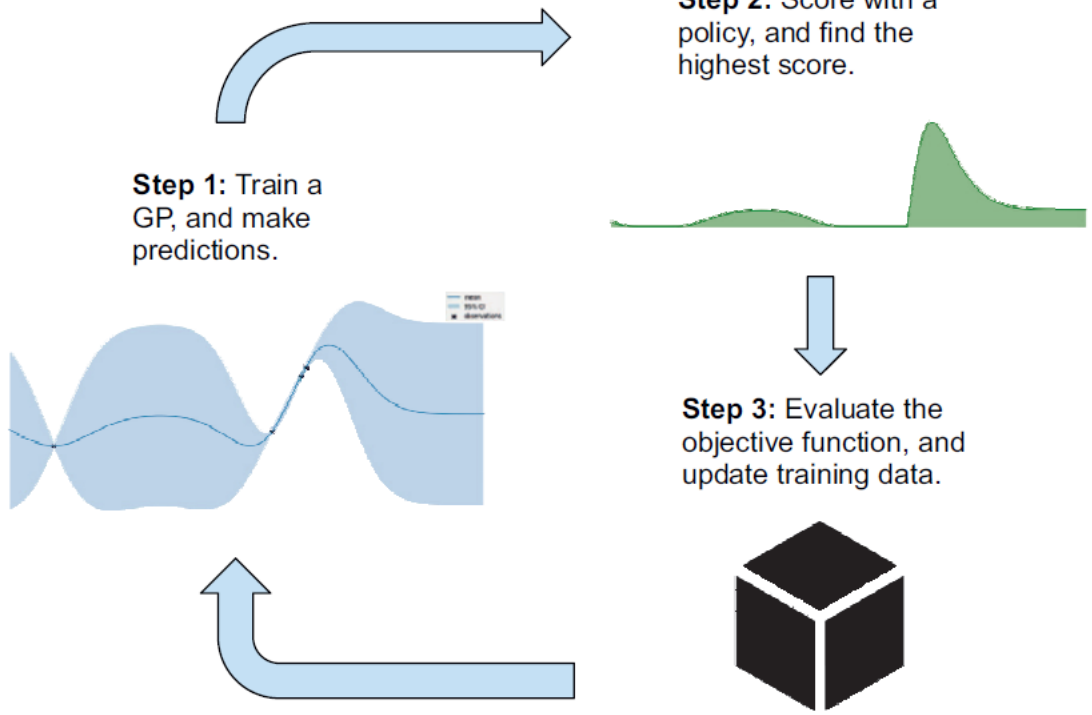
Covariance matrix

$$p(\mathbf{y}|\Sigma) \propto \exp\left(-\tfrac{1}{2}\mathbf{y}^\intercal\Sigma^{-1}\mathbf{y}\right) \qquad \Sigma = \begin{bmatrix} 1 & .7 \\ .7 & 1 \end{bmatrix}$$

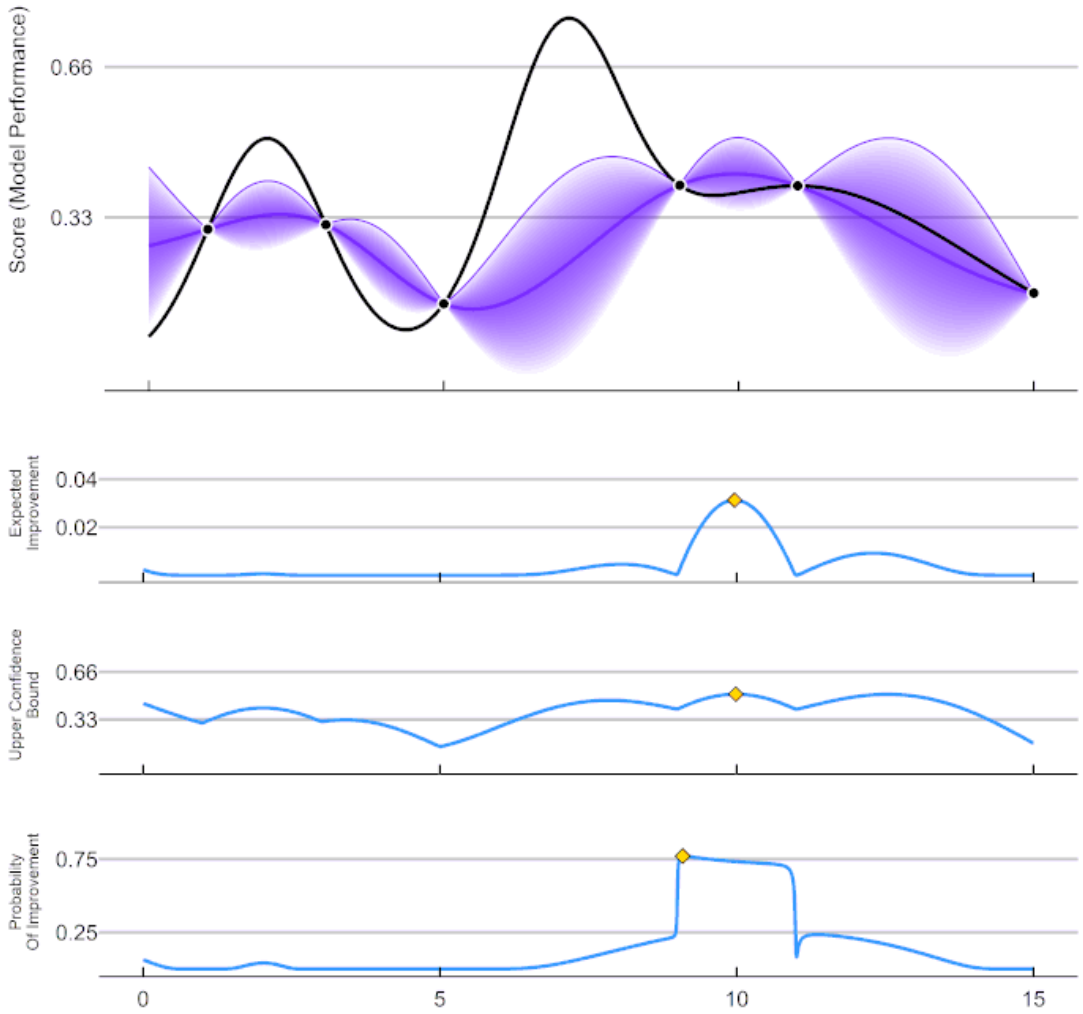


APPROXIMATING A TARGET FUNCTION





APPROXIMATING A TARGET FUNCTION



RESEARCH EXAMPLES

Efficient Online Testing for DNN-Enabled Systems using Surrogate-Assisted and Many-Objective Optimization

Publisher: IEEE Cite This PDF

Fitash Ul Haq ; Donghwan Shin ; Lionel Briand **All Authors**

Conferences > 2022 IEEE International Confe...

Cost-effective Simulation-based Test Selection in Self-driving Cars Software with SDC-Scissor

Publisher: IEEE Cite This PDF

Christian Birchler ; Nicolas Ganz ; Sajad Khatiri ; Alessio Gambi ; Sebastiano Panichella **All Authors**

Efficient online testing for DNN-enabled systems using surrogate-assisted and many-objective optimization

Authors: Fitash Ul Haq, Donghwan Shin, Lionel Briand | Authors Info & Claims

ICSE '22: Proceedings of the 44th International Conference on Software Engineering • Pages 811 - 822
https://doi.org/10.1145/3510003.3510188

CONCLUSIONS

- Fuzzing is good when input seed are known
- Evolutionary search is good for exploring the search space globally
- Given simulations are time consuming, the efficiency of GA should be increased
- Bayesian optimization is a popular approach for building surrogate models
- Evolutionary search can be combined with surrogate modeling to increase efficiency

POLYTECHNIQUE MONTRÉAL

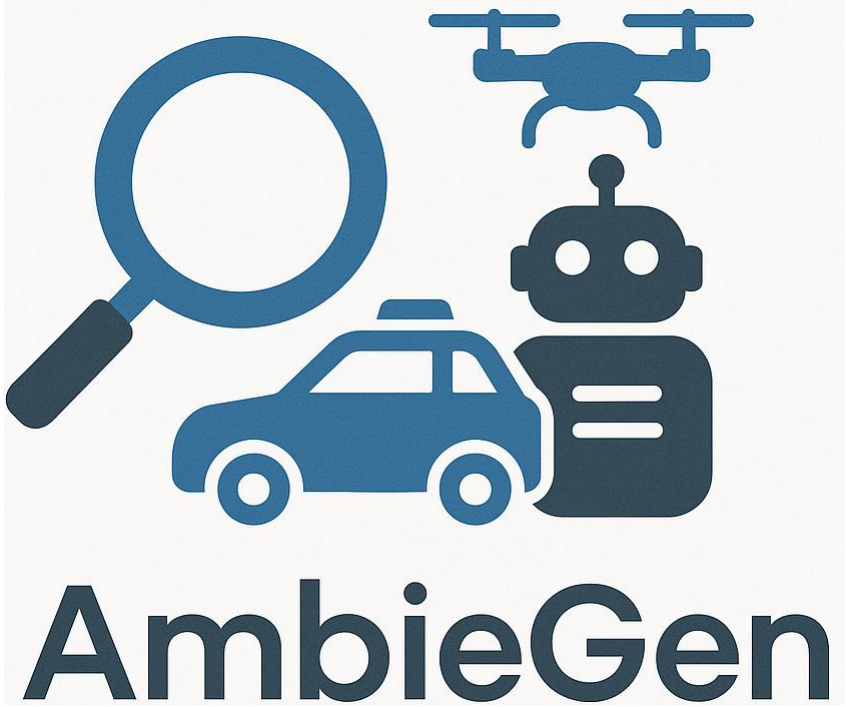
TECHNOLOGICAL UNIVERSITY

Q & A

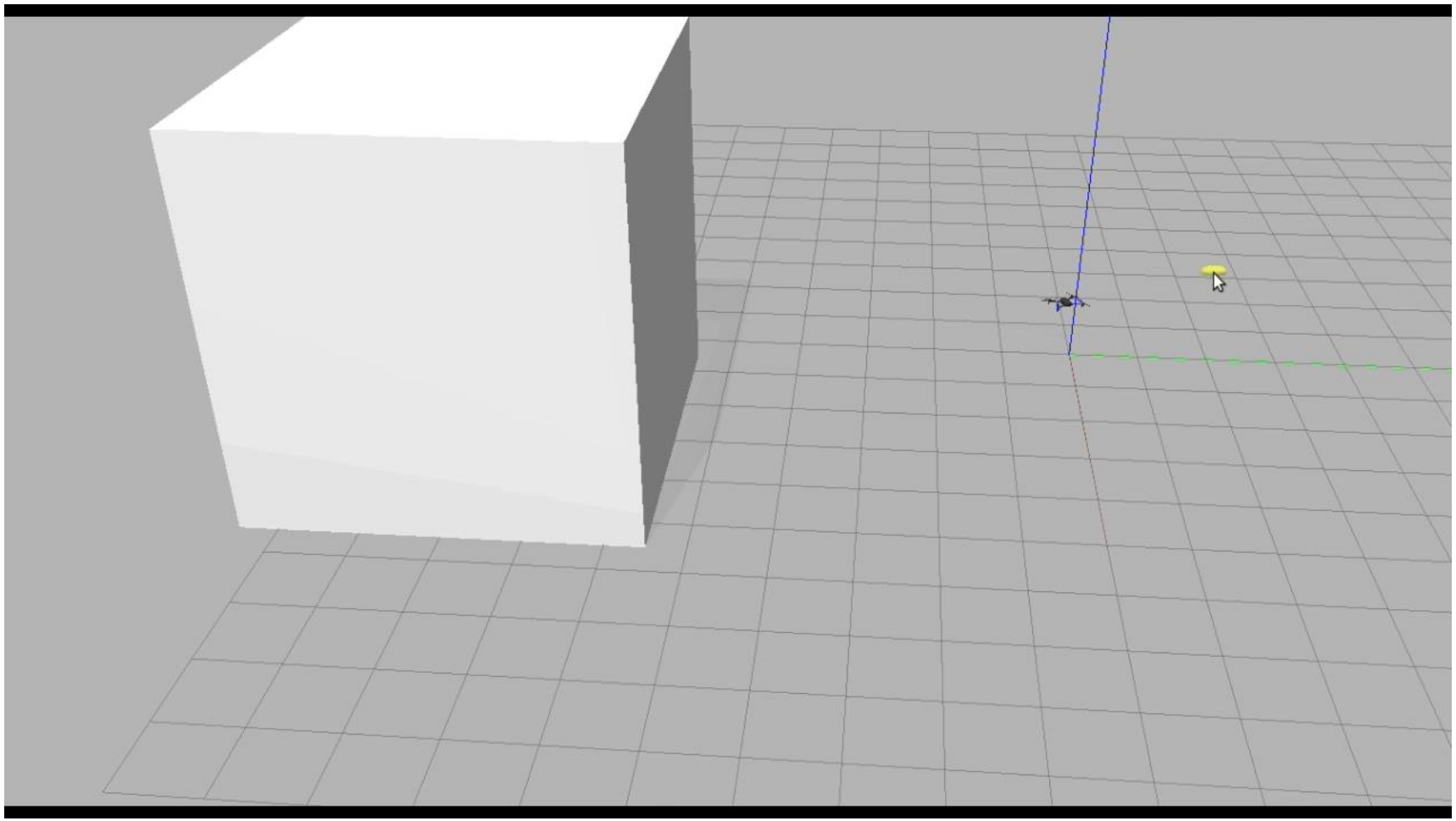
HANDS ON SESSION

AMBIEGEN TOOL

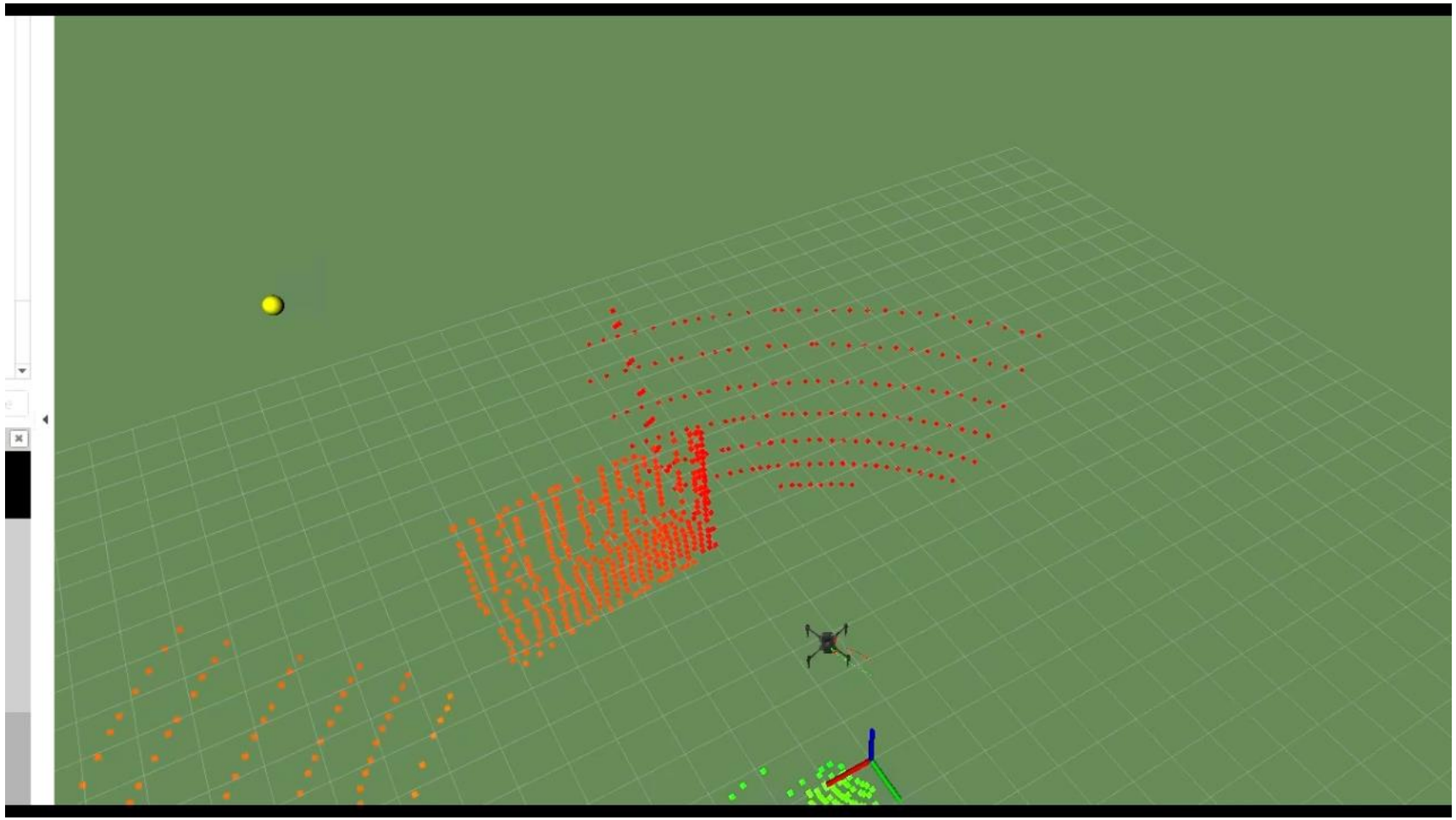
https://ambiegen.readthedocs.io/en/latest/



SYSTEM UNDER TEST



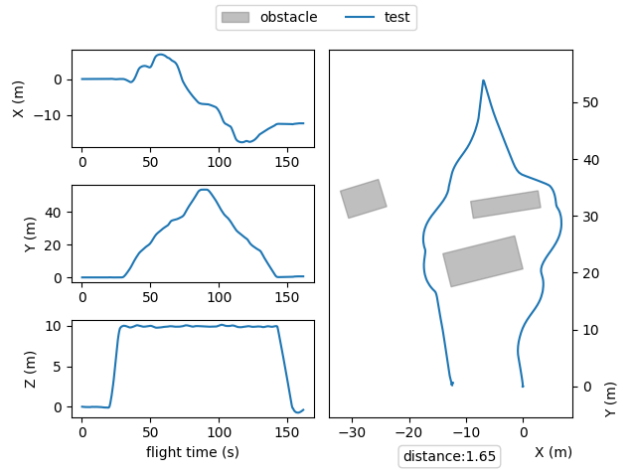
SYSTEM UNDER TEST

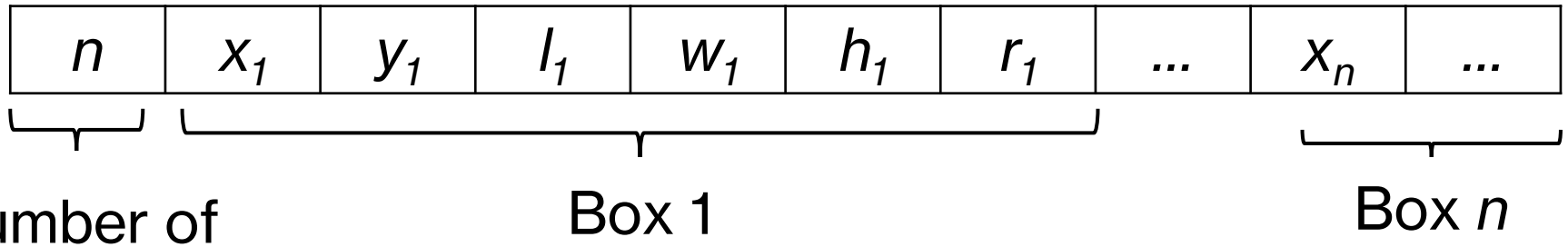


SYSTEM UNDER TEST

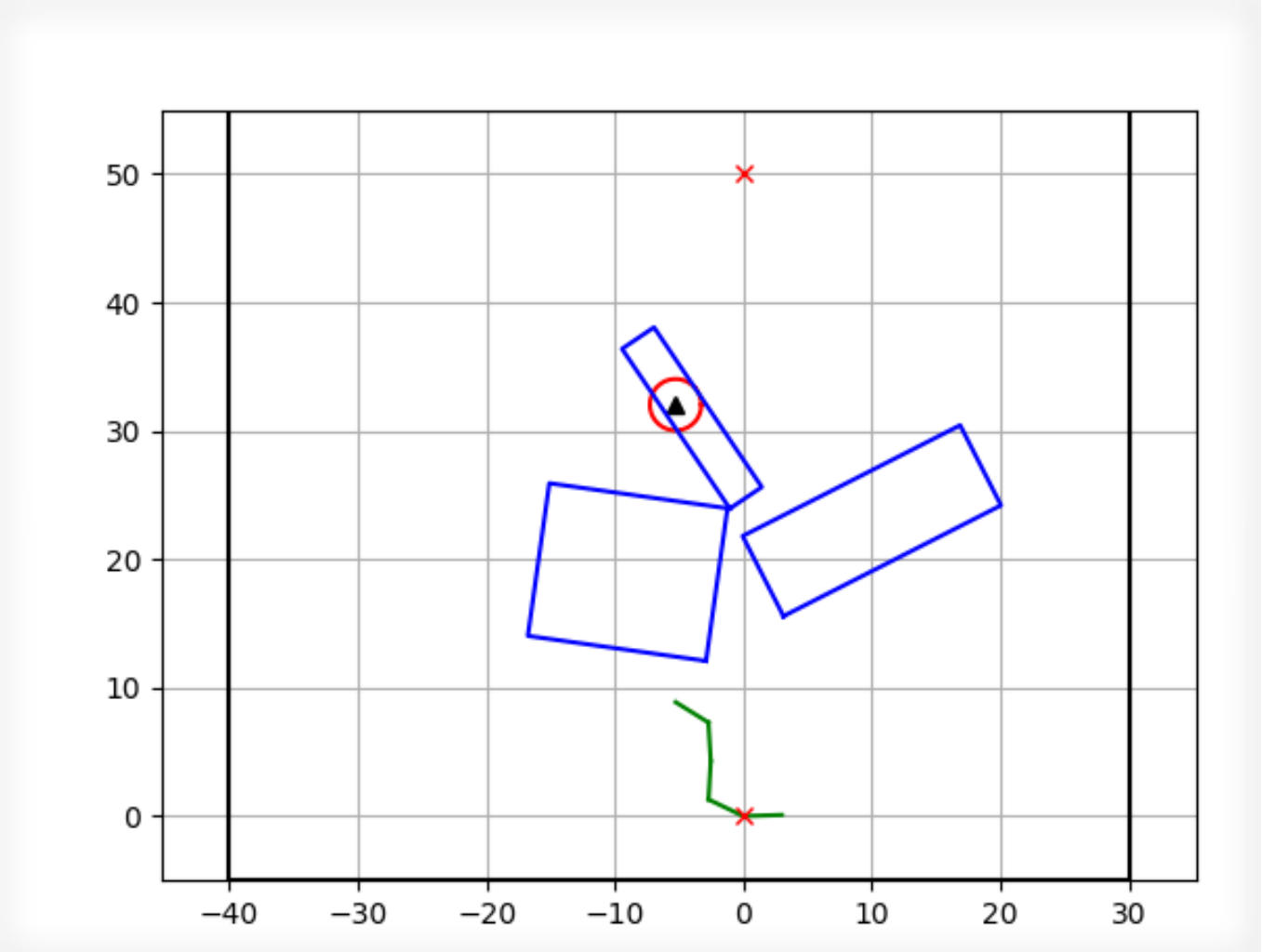
- 1 objective
- 3 constraints
- 19 dimensions
- ~120 s per evaluation

Valid test case





FITNESS FUNCTION



FRAMEWORK OVERVIEW

AbstractTester

```
AbstractTester(
    name="abstract_test_generator", config_file=None
)
```

AbstractEvolutionaryTester

```
AbstractEvolutionaryTester(
    name="evlutionary_test_generator", config_file=None
)
```

Methods:

Name
initialize_test_generator
initialize_test_executors
set_up_search_algorithm
run_optimization
start

set_up_search_algorithm	Initializes the search algorithm.
initialize_parameters	Sets up the parameters for the evolutionary algorithm.
configure_algorithm	Sets up the evolutionary algorithm
initialize_problem	Initializes the pymoo optimization problem.
run_optimization	Executes the optimization process using the configured algorithm.
initialize_test_generator	Abstract method to initialize the test generator, should be implemen
initialize_test_executors	Abstract method to initialize the test executors, should be implemen

```yaml
tester: search_based  #

common:
  seed: None
  termination: "n_gen"
  budget: 100

search_based:
  pop_size: 100
  algorithm: "ga"
  crossover: "sbx"
  mutation: "pm"
  crossover_prob: 0.9
  mutation_prob: 0.4
  problem_name: 'uav'
```

FRAMEWORK OVERVIEW

AbstractGenerator

```
AbstractGenerator(name='AbstractGenerator')
```

Methods:

Name
cmp_func
genotype2phenotype
generate_random_test
is_valid
visualize_test
phenotype2genotype

AbstractExecutor

```
AbstractExecutor(
    generator, results_path=None, min_fitness=0.0
)
```

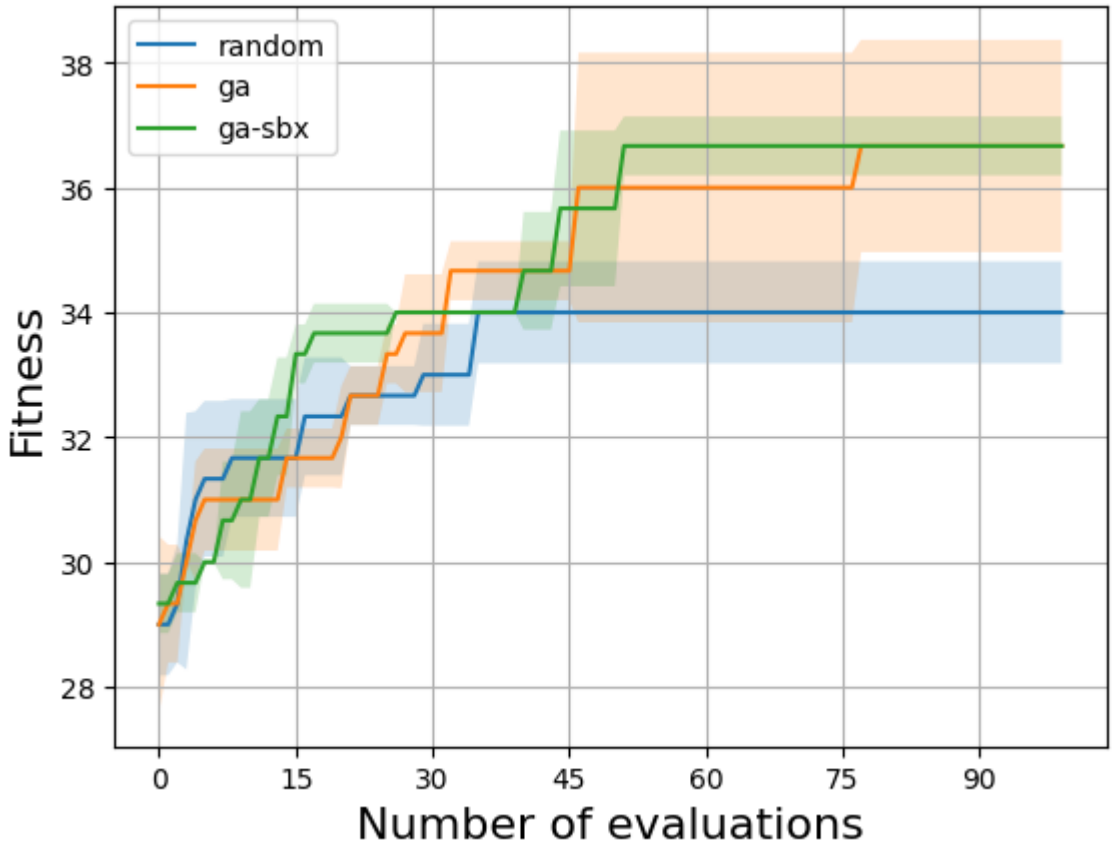
Methods:

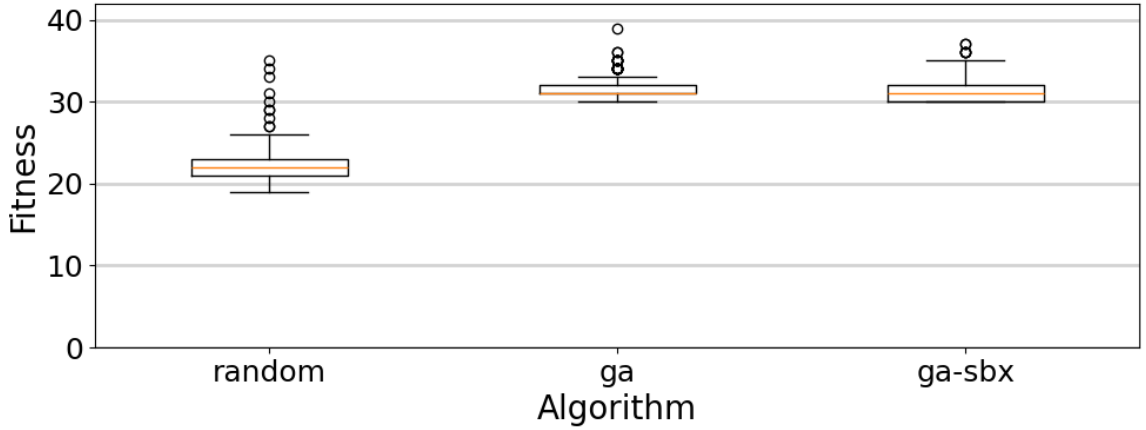
Name
execute_test
_execute

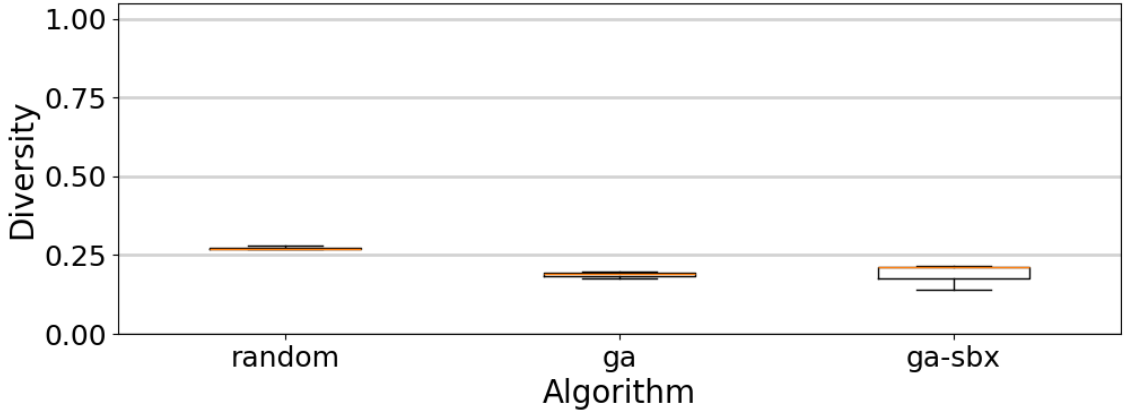
```
def _execute(self, test) -> float:
    fitness = 0
    self.uav_test_dict[self.exec_counter] = {}
    self.uav_test_dict[self.exec_counter]["test"] = test

    try:
        self.n_sim_evals += 1
        trajectory = test.execute()
        data = trajectory.to_data_frame()
        #print(data)
        x_coord = list(data[:, 1])
        y_coord = list(data[:, 2])
        z_coord = list(data[:, 3])
        yaw = list(data[:, 4])
```

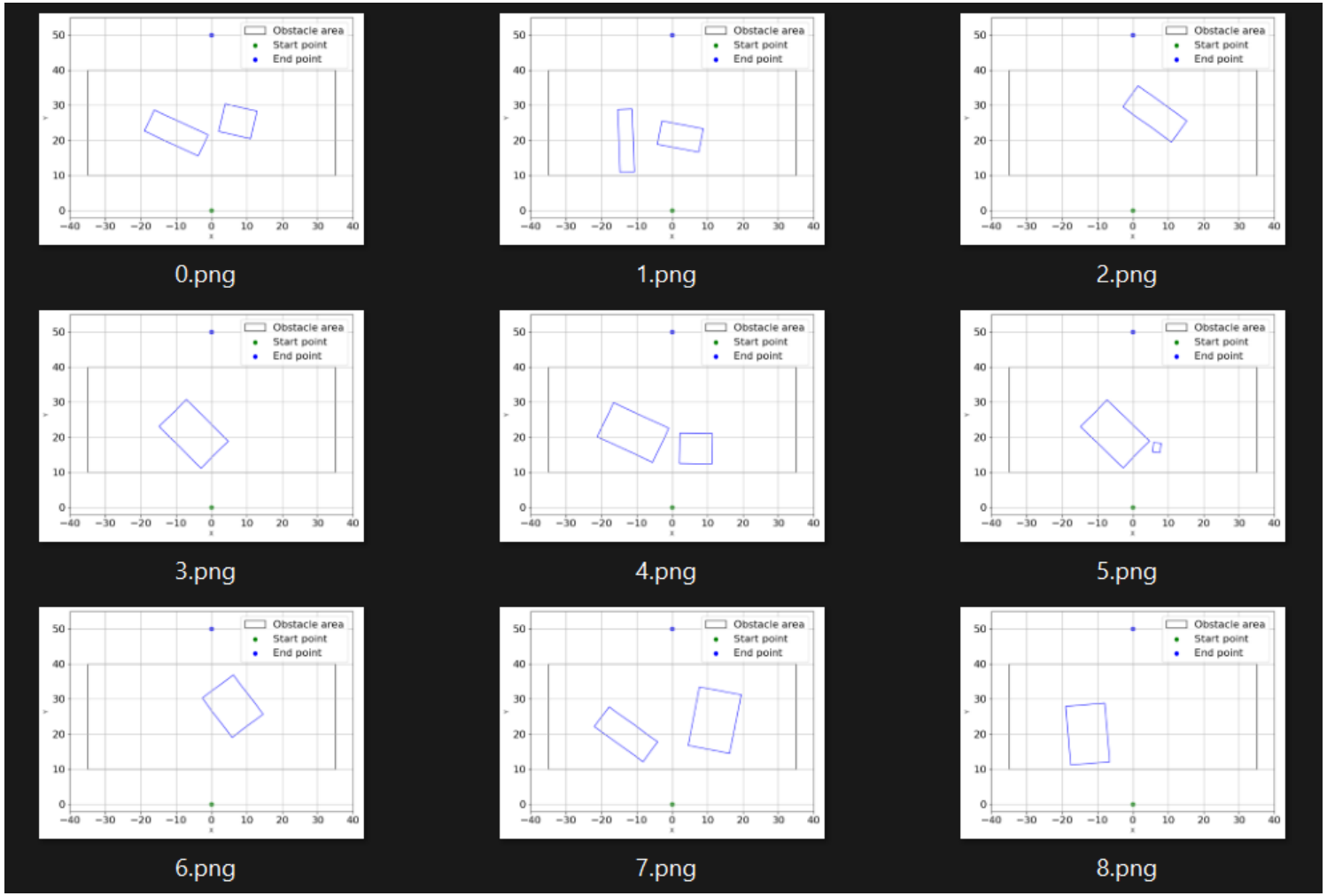
FRAMEWORK OVERVIEW







FRAMEWORK OVERVIEW



POLYTECHNIQUE MONTRÉAL

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https://github.com/swat-lab-optimization

Q & A