Hochschule
Bonn-Rhein-Sieg
University of Applied Sciences

b-it Bonn-Aachen International Center for Information Technology

Institute for AI and Autonomous Systems

Data-Driven Robot Software

How Learning-Based Components Fit Into the Puzzle

Dr. Alex Mitrevski
Master of Autonomous Systems

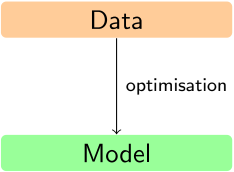
Structure

- Software development and machine learning
- Methods for data-driven development

Software Development and Machine Learning

What Do We Mean by Learning?

- Learning is a paradigm based on which **models — their parameters or structure — are extracted based on data**
- In robotics, we want a robot to **learn how to act by observing — and interacting with — the environment**
- Typically, learning is performed by **solving an optimisation problem over the model's parameters**



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Increased autonomy

In principle, learning-based robot components can be improved autonomously, without a need to make modifications to the underlying implementation

Simple Learning Example: Linear Regression

- Suppose that we are given **a set of n points** $\mathcal{D} = \{(x_i, y_i) \mid 1 \leq i \leq n\}$, and we want to **find the parameters of the best line that fits them**

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- We can represent a line by parameters $\boldsymbol{\theta} = (m, c)$ as $y = mx + c$, where m is a slope and c the intercept, and we can define the **mean-squared error as a loss function**:

$$\mathcal{L}(\mathcal{D}, \boldsymbol{\theta}) = \frac{1}{n} \sum_{i=1}^{n} (y_i - (mx_i + c))^2$$

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- This component can then be integrated into robot software, e.g. for wall detection from laser scan data during navigation

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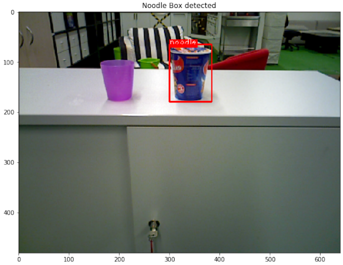

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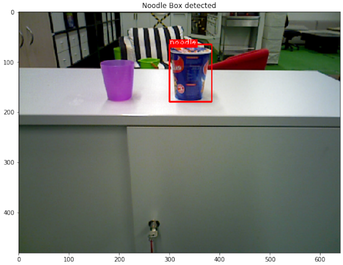

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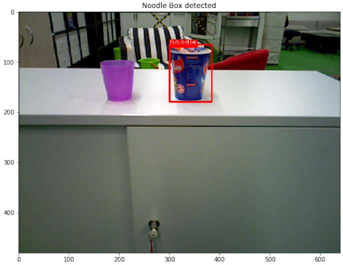

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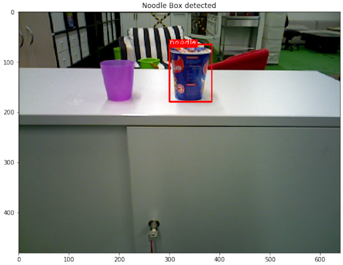

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- The classifier can then be integrated into a robot's scene understanding component

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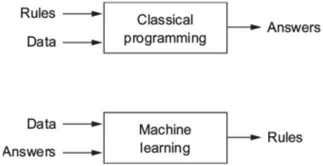

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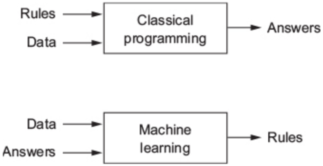

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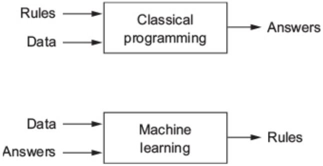

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  - One of the main reasons why learning is so readily accepted by many roboticists
- On a smaller scale, **it affects the development and integration of individual robot components**
- In principle, learning can also **affect the complete development process**
  - Learning can be seen as a form of programming — the objective is not writing code, but the design of behaviours and the collection of data for learning those

Complex Robot Behaviours by Objective Maximisation

- Programming robots can replace explicit behaviour programming with a process of **learning to satisfy a mathematical objective function**, which involves:
  - **Defining an objective function** to be satisfied
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  - **Defining an objective function** to be satisfied
  - **Training the robot** (in simulation or the real world) to optimise the objective function
- This reduces the software development burden, **letting the robot do the hard work** instead
  - Development effort is still needed for the optimisation algorithms

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- Learning from demonstration requires two aspects:
  1. **Demonstrations by a human expert**
  2. A representation that **converts demonstrations into a form that a robot can use for subsequent execution**
- The primary benefit of learning from demonstrations is that **end users can influence the behaviour of the robot** (i.e. they can program the robot — without writing code)

Traditional vs. Data-Driven Software Development

Traditional

1. Design an **analytical model** of a desired behaviour
2. Decide on a **representation** for the behaviour (e.g. state machine)
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1. Design an **optimisation criterion** for the desired behaviour
2. Decide on a **model class** for representing the behaviour (e.g. neural network)
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4. Create a **data collection strategy** for learning the behaviour
5. Collect data and learn the associated model

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In both cases, the processes may need to be iterated, particularly to incorporate evaluation results

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Which of these is appropriate to use depends on multiple factors, such as **the maturity of analytical models**, **the data collection requirements**, and **the safety requirements**

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- The integration of learning components is typically easy — provided that the **software architecture is modular enough**
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- Integration simplified by **de facto standard learning frameworks**
  - This encourages reuse-oriented development

Learning Component Integration Example[1]

Detection interface

```
class DetectionHandler(object):
    def __init__(self, detection_class,
                 class_annotation_file,
                 kwargs_file):
        self._detector = detection_class(class_file=class_annotation_file, model_kwargs_file=kwargs_file)

    def detect_objects(self, img):
        predictions = self._detector.detect([img])
        if len(predictions) < 1:
            raise RuntimeError('No predictions for image')
        bounding_boxes, classes, confidences \
            = ImageDetectorBase.prediction_to_bounding_boxes(predictions[0], self._detector.class_colors)
        return bounding_boxes, classes, confidences
```

High-level detection interface over ROS

```
class DetectionServer(object):
    def __init__(self, **kwargs):
        self._detection_handler = DetectionHandler(kwargs.get('detection_class', None),
                                                   kwargs.get('class_annotation_file', None),
                                                   kwargs.get('kwargs_file', None))

    def execute(self):
        cloud_msg = rospy.wait_for_message(self._cloud_topic, PointCloud2, timeout=self._timeout_s)
        img_msg = cloud_msg_to_image_msg(cloud_msg)
        bounding_boxes, classes, confidences = self._detection_handler.process_image_msg(img_msg)
```

[1] The examples on this slide are adapted from https://github.com/b-it-bots/mas_perception_libs

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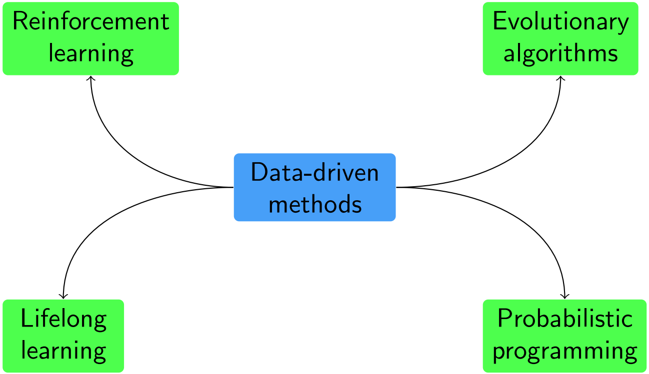
- Traditional software development practices are also important in machine learning itself
  - Most open-source learning frameworks follow object-oriented programming principles
- **Using learning is not an invitation for developing bad software**
  - The interaction with learning-based components is still done through programs that we need to develop and maintain
  - Learning-based components need to be tested, deployed, and maintained just as any other software

Methods for Data-Driven Development

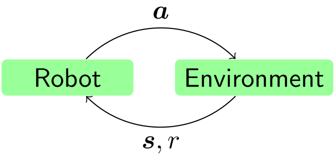
Methods Overview

- Various data-driven development methods can useful for robotics; we will look at the following ones on the next slides:



- Note that this figure is not a complete overview — more detailed information about learning frameworks is provided in the "Robot Learning" course

Reinforcement Learning (RL)



- The objective of RL is to learn an **execution policy** π **given observations of the form** $(\boldsymbol{s}_t, \boldsymbol{a}_t, \boldsymbol{s}_{t+1}, r_t)$, where $\boldsymbol{s} \in S$ are states, $\boldsymbol{a} \in A$ are actions, and $r \in \mathbb{R}$ is a reward

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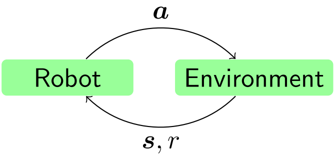

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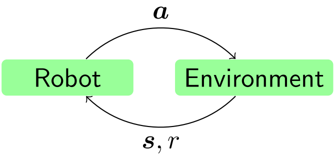

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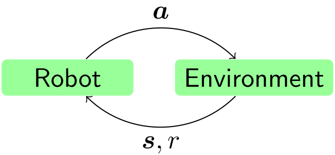

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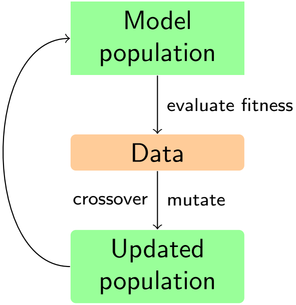
- RL is widely used in robotics

Evolutionary Algorithms



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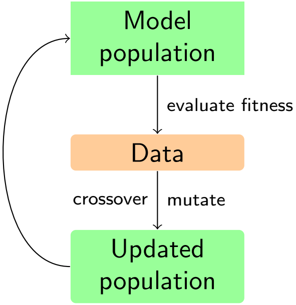

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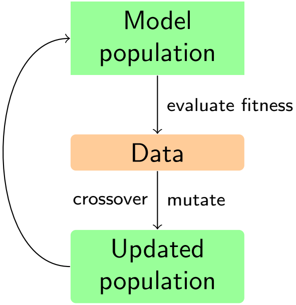

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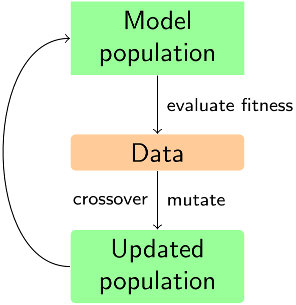

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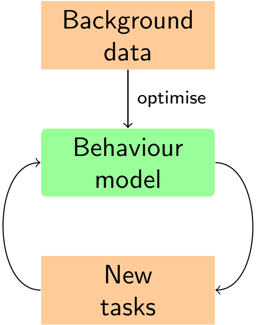
- This process can result in either **a single model to drive the behaviour** or **a collection of behaviour models** — potentially suitable for different cases
- Evolutionary optimisation is also a form of automatic program synthesis and can be used for **optimising model structure**

Neural Networks (NNs) and Lifelong Learning



- When representing robot behaviour, NNs can be seen as programs that **process an input, such as sensor data, to produce an output, such as robot motions**
  - In fact, the RL policy is often represented by an NN

[2] R. Firoozi et al., "Foundation Models in Robotics: Applications, Challenges, and the Future", *CoRR*, vol. abs/2312.07843, Dec. 2023. Available: https://arxiv.org/abs/2312.07843

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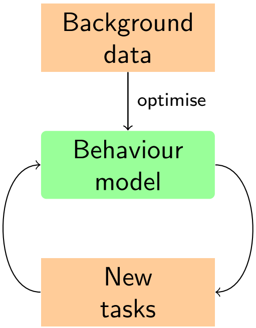

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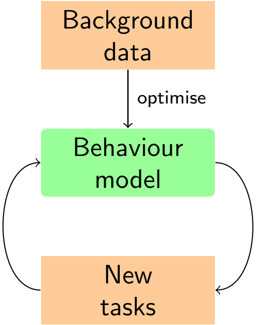
Neural Networks (NNs) and Lifelong Learning



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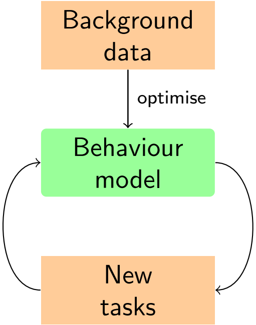

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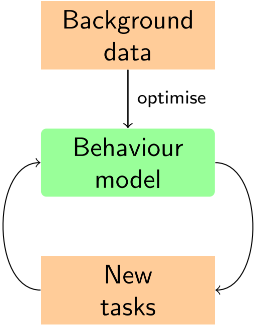

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- **Probabilistic reasoning is at the core of intelligent robots** (see AMR), and probabilistic programming can simplify the integration of probabilistic models into robot programs

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Augmented data

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- Short of a larger real dataset, **data augmentation** is typically used to increase the coverage of training data
  - Augmentation is a process in which existing data items are used to create new, artificial training examples

What Do We Lose With Data-Driven Development?

Full control over and understanding of our systems

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The fun and creativity of software development

Developing large software can be a very creative task — relying on data-driven frameworks can simplify the development, but also reduce some of the task's creativity

Robot Software Development in Future (Own Opinion)

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- **The potentials of learning for robotics** have to be acknowledged
  - Learning makes it possible to implement robot functionalities that have otherwise been very difficult to achieve
- But it is important to **recognise the limitations of learning-based frameworks** with respect to safety-critical systems
  - We can only develop better learning-based systems by actively using learning in robotics and identifying problems that we can solve