



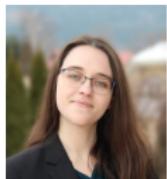
Neural Network Verification with Vehicle

Ekaterina Komendantskaya and Matthew Daggitt (today's presentors), on behalf of the Vehicle team

The Vehicle Team



Matthew Daggitt



Natalia Slusarz



Ben Coke



Wen Kokke



Bob Atkey



Luca Arnaboldi



Katya K



Marco Casadio



Jeonghyeon Lee



Table of Contents



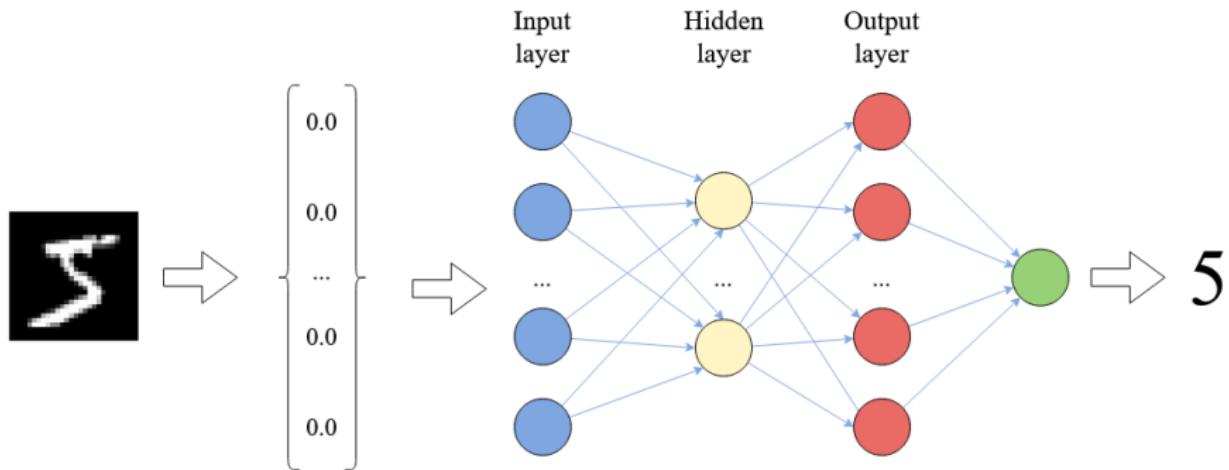
Neural Network Verification: overview of the new domain

The lifecycle of neural network verification

Challenges and Languages

Vehicle's Role and Purpose of this Tutorial

Neural nets for classification



Formally,

a neural network is a function $N : R^n \rightarrow R^m$.

Neural networks



... are ideal for “perception” tasks:

- ▶ approximate functions when exact solution is hard to get
- ▶ tolerant to noisy and incomplete data

Neural networks



... are ideal for “perception” tasks:

- ▶ approximate functions when exact solution is hard to get
- ▶ tolerant to noisy and incomplete data

Neural networks



... are ideal for “perception” tasks:

- ▶ approximate functions when exact solution is hard to get
- ▶ tolerant to noisy and incomplete data

Neural networks



... are ideal for “perception” tasks:

- ▶ approximate functions when exact solution is hard to get
- ▶ tolerant to noisy and incomplete data

BUT

- ▶ solutions not easily conceptualised (**lack of explainability**)
- ▶ prone to a new range of safety and security problems:

Neural networks



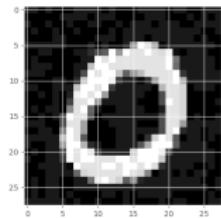
... are ideal for “perception” tasks:

- ▶ approximate functions when exact solution is hard to get
- ▶ tolerant to noisy and incomplete data

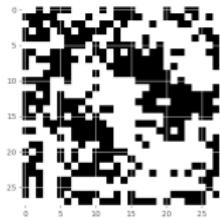
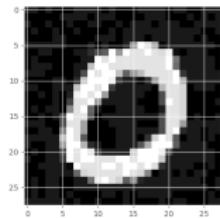
BUT

- ▶ solutions not easily conceptualised (**lack of explainability**)
- ▶ prone to a new range of safety and security problems:
 - adversarial attacks
 - data poisoning
 - catastrophic forgetting

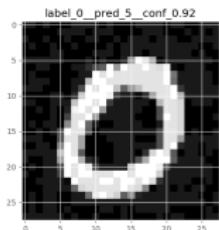
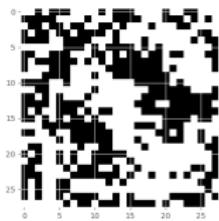
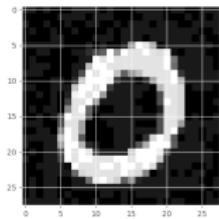
One example: Adversarial Attacks



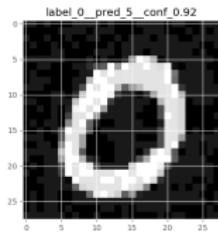
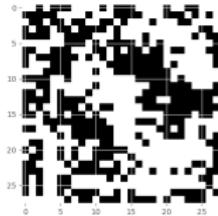
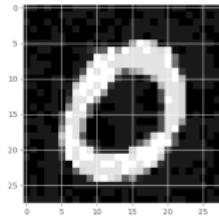
One example: Adversarial Attacks



One example: Adversarial Attacks

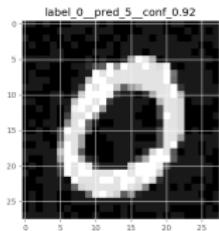
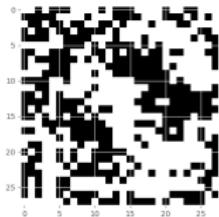
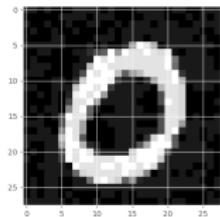


One example: Adversarial Attacks



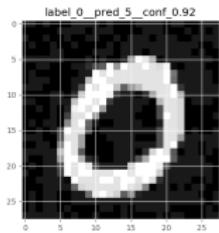
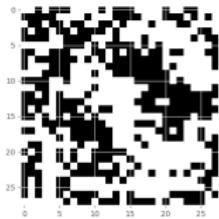
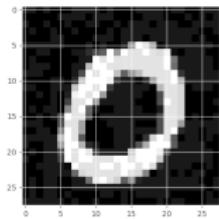
the perturbations are imperceptible to human eye

One example: Adversarial Attacks



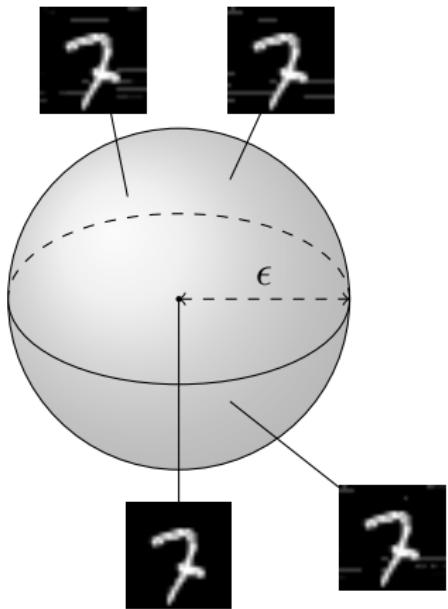
the perturbations are imperceptible to human eye
attacks transfer from one neural network to another

One example: Adversarial Attacks



the perturbations are imperceptible to human eye
attacks transfer from one neural network to another
affect any domain where neural networks are applied

Verification Property: “ ϵ -ball robustness”



An ϵ -ball $\mathbb{B}(\hat{\mathbf{x}}, \epsilon) = \{\mathbf{x} \in \mathbb{R}^n : |\hat{\mathbf{x}} - \mathbf{x}| \leq \epsilon\}$

Classify all points in $\mathbb{B}(\hat{\mathbf{x}}, \epsilon)$ “robustly”.

Another example property: ACAS Xu



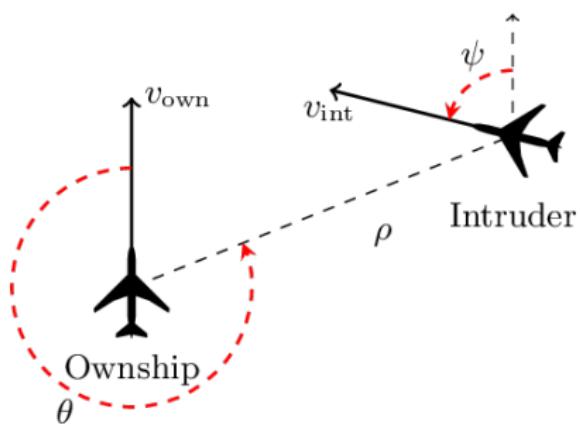
A collision avoidance system for unmanned autonomous aircraft.

Inputs:

- ▶ Distance to intruder, ρ
- ▶ Angle to intruder, θ
- ▶ Intruder heading, φ
- ▶ Speed, v_{own}
- ▶ Intruder speed, v_{int}

Outputs:

- ▶ Clear of conflict
- ▶ Strong left
- ▶ Weak left
- ▶ Weak right
- ▶ Strong right





The system was originally implemented as a 2Gb lookup table but was replaced with a neural network in order to improve size and latency requirements.



The system was originally implemented as a 2Gb lookup table but was replaced with a neural network in order to improve size and latency requirements.

10 different specified properties in total.



The system was originally implemented as a 2Gb lookup table but was replaced with a neural network in order to improve size and latency requirements.

10 different specified properties in total.

Definition (ACAS Xu: Property 1)

If the intruder is distant and is significantly slower than the ownship, the score of a COC advisory will always be below a certain fixed threshold.



The system was originally implemented as a 2Gb lookup table but was replaced with a neural network in order to improve size and latency requirements.

10 different specified properties in total.

Definition (ACAS Xu: Property 1)

If the intruder is distant and is significantly slower than the ownship, the score of a COC advisory will always be below a certain fixed threshold.

$$(\rho \geq 55947.691) \wedge (v_{own} \geq 1145) \wedge (v_{int} \leq 60)$$

\Rightarrow the score for COC is at most 1500



More Generally

Given $N : R^n \rightarrow R^m$

Verification of such functions most commonly boils down to specifying admissible intervals for the function's output given an interval for its inputs.



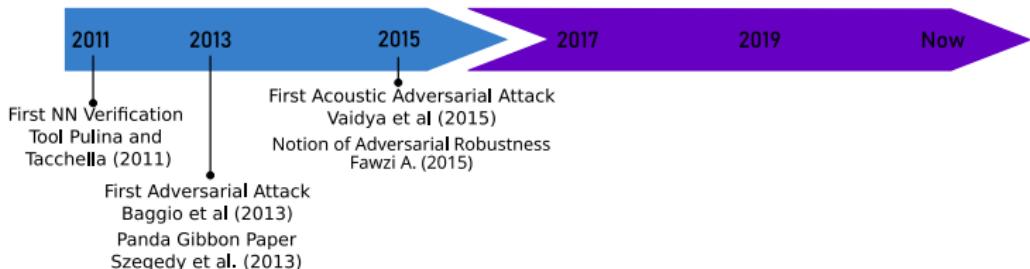
More Generally

Given $N : R^n \rightarrow R^m$

Verification of such functions most commonly boils down to specifying admissible intervals for the function's output given an interval for its inputs.

- 📄 Casadio, M., Komendantskaya, E., Daggitt, M.L., Kokke, W., Katz, G., Amir, G., Refaeli, I.: Neural network robustness as a verification property: A principled case study. In: Computer Aided Verification (CAV 2022).

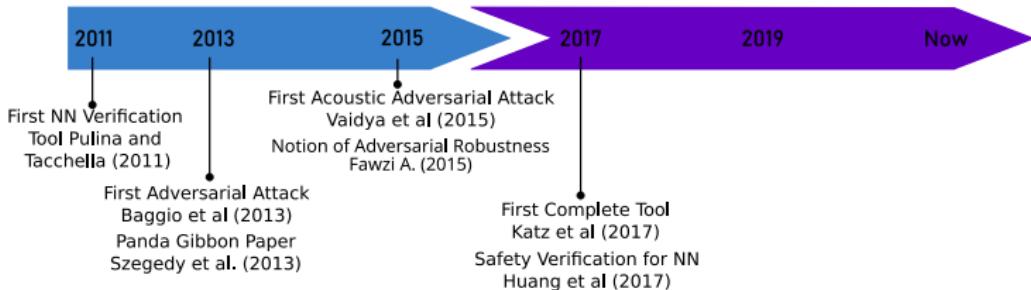
Overview of The Verification Landscape



What tools are available?
2015



Overview of The Verification Landscape



I have this specification
I want to verify!



property specification

What tools are available?
2017



approximate



adverserial

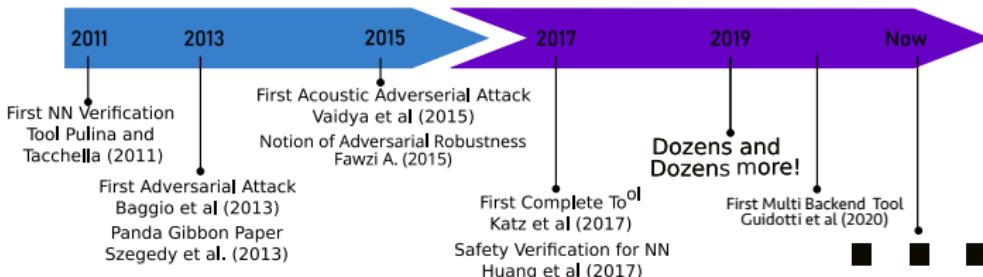


complete



others

Overview of The Verification Landscape



What tools are available?
2023



Current Verifier Landscape



A whole range of domain-specific verifiers exist:



Current Verifier Landscape

A whole range of domain-specific verifiers exist:

- ▶ Marabou (SMT technology)



Current Verifier Landscape

A whole range of domain-specific verifiers exist:

- ▶ Marabou (SMT technology)
- ▶ ERAN (abstract interpretation + MILP)



Current Verifier Landscape

A whole range of domain-specific verifiers exist:

- ▶ Marabou (SMT technology)
- ▶ ERAN (abstract interpretation + MILP)
- ▶ Verisig (interval arithmetic)
- ▶ AlphaBetaCROWN (linear bound propagation)
- ▶ ...

International Standards and Competitions

<https://www.vnnlib.org/>



Current Verifier Landscape

A whole range of domain-specific verifiers exist:

- ▶ Marabou (SMT technology)
- ▶ ERAN (abstract interpretation + MILP)
- ▶ Verisig (interval arithmetic)
- ▶ AlphaBetaCROWN (linear bound propagation)
- ▶ ...

International Standards and Competitions

<https://www.vnnlib.org/>

Marabou is our current choice as it is complete, and the set of expressible queries is large!

-  Guy Katz, Clarke Barrett, D. Dill, K. Julian, and M. Kochenderfer. Reluplex: An Efficient SMT Solver for Verifying Deep Neural Networks. In CAV, 2017.

Table of Contents



Neural Network Verification: overview of the new domain

The lifecycle of neural network verification

Challenges and Languages

Vehicle's Role and Purpose of this Tutorial

The lifecycle of neural network verification



Property

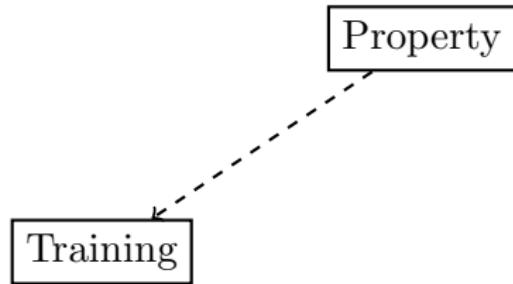
The lifecycle of neural network verification



Property

Training

The lifecycle of neural network verification

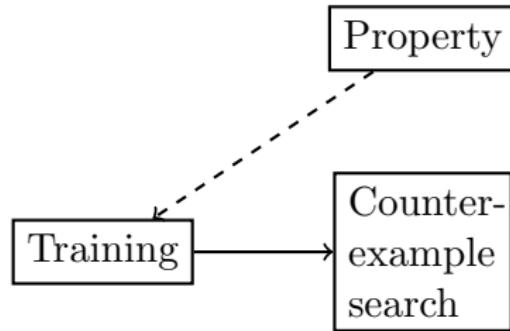


DL2

ACT

etc.

The lifecycle of neural network verification

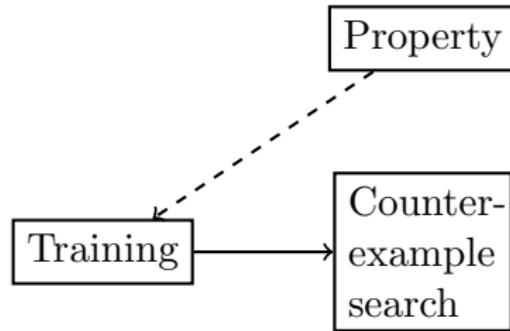


DL2

ACT

etc.

The lifecycle of neural network verification

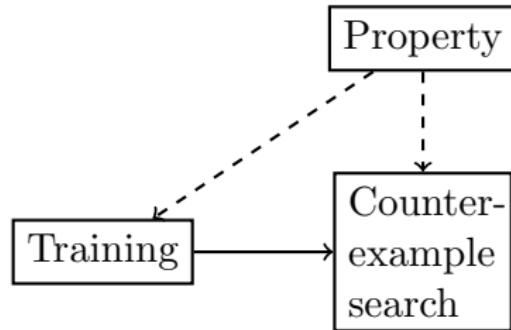


DL2

ACT

etc.

The lifecycle of neural network verification



DL2

ACT

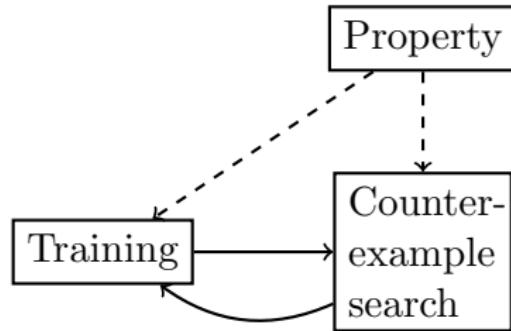
etc.

PGD

FGSM

etc.

The lifecycle of neural network verification



DL2

ACT

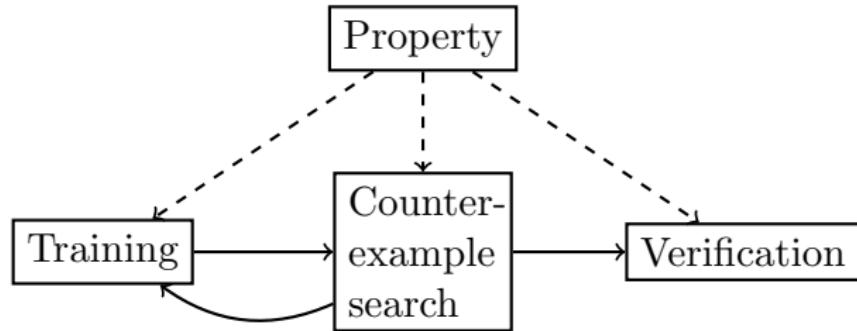
etc.

PGD

FGSM

etc.

The lifecycle of neural network verification



DL2

ACT
etc.

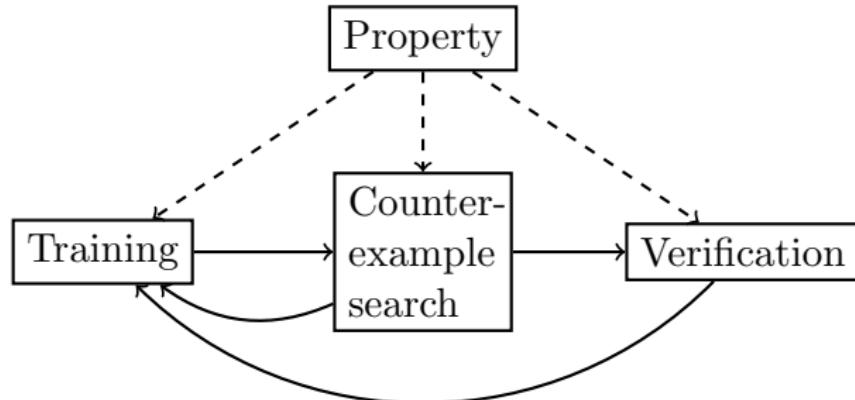
PGD

FGSM
etc.

Marabou

Eran
etc.

The lifecycle of neural network verification



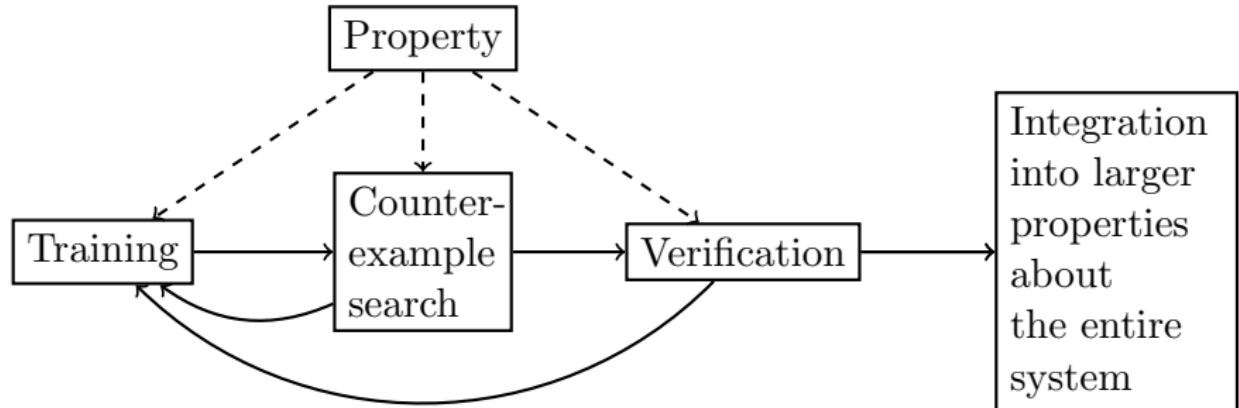
DL2

ACT
etc.

PGD
FGSM
etc.

Marabou
Eran
etc.

The lifecycle of neural network verification



DL2
ACT
etc.

PGD
FGSM
etc.

Marabou
Eran
etc.

Table of Contents



Neural Network Verification: overview of the new domain

The lifecycle of neural network verification

Challenges and Languages

Vehicle's Role and Purpose of this Tutorial

Challenges the area faces



- ▶ Theory: finding appropriate verification properties

Challenges the area faces



- ▶ Theory: finding appropriate verification properties
- ▶ Solvers: undecidability of non-linear real arithmetic and scalability of neural network verifiers



Challenges the area faces

- ▶ Theory: finding appropriate verification properties
- ▶ Solvers: undecidability of non-linear real arithmetic and scalability of neural network verifiers
- ▶ ML: understanding and integrating property-driven training

Challenges the area faces



- ▶ Theory: finding appropriate verification properties
- ▶ Solvers: undecidability of non-linear real arithmetic and scalability of neural network verifiers
- ▶ ML: understanding and integrating property-driven training
- ▶ Programming: finding the right languages to support these developments

Challenges the area faces



- ▶ Theory: finding appropriate verification properties
- ▶ Solvers: undecidability of non-linear real arithmetic and scalability of neural network verifiers
- ▶ ML: understanding and integrating property-driven training
- ▶ Programming: finding the right languages to support these developments
- ▶ Complex systems: integration of neural net verification into complex systems



Some of these problems are aggravated by insufficient programming language or API support

Lets look under the hood...



Training framework: DL2

```
126 class RobustnessConstraint(Constraint):
127
141     def get_domains(self, x_batches, y_batches):
142         assert len(x_batches) == 1
143         n_batch = x_batches[0].size()[0]
144
145         return [[Box(np.clip(x_batches[0][i].cpu().numpy() - self.eps, 0, 1),
146                    np.clip(x_batches[0][i].cpu().numpy() + self.eps, 0, 1))
147                  for i in range(n_batch)]]
148
149     def get_condition(self, z_inp, z_out, x_batches, y_batches):
150         n_batch = x_batches[0].size()[0]
151         z_out = transform_network_output(z_out, self.network_output)[0]
152         #z_logits = F.log_softmax(z_out[0], dim=1)
153
154         pred = z_out[np.arange(n_batch), y_batches[0]]
155
156         limit = torch.FloatTensor([0.3])
157         if self.use_cuda:
158             limit = limit.cuda()
159         return dl2.GEQ(pred, torch.log(limit))
```



Fischer, M., Balunovic, M., Drachsler-Cohen, D., Gehr, T., Zhang, C., and Vechev, M. T. DL2: training and querying neural networks with logic. In Proc. of the 36th Int. Conf. Machine Learning, ICML 2019

Training framework: ART



```
333     @classmethod
334     def property6a(cls, dom: AbsDom):
335         p = AcasProp(name='property6a', dom=dom, safe_fn='cols_is_min', viol_fn='cols_not_min',
336                      fn_args=[AcasOut.CLEAR_OF_CONFLICT])
337         p.set_input_bound(AcasIn.RHO, new_low=12000, new_high=62000)
338         p.set_input_bound(AcasIn.THETA, new_low=0.7, new_high=3.141592)
339         p.set_input_bound(AcasIn.PSI, new_low=-3.141592, new_high=-3.141592 + 0.005)
340         p.set_input_bound(AcasIn.V_OWN, new_low=100, new_high=1200)
341         p.set_input_bound(AcasIn.V_INT, new_low=0, new_high=1200)
342         p.set_all_applicable_as(False)
343         p.set_applicable(1, 1, True)
344         return p
```



Lin, X., Zhu, H., Samanta, R., and Jagannathan, S. (2020). Art: Abstraction refinement-guided training for provably correct neural networks. In FMCAD 2020

Verification framework: Marabou



```
def test_acas_1_1_normalize():
    """
    Test the 1,1 experimental ACAS Xu network.
    By passing "normalize=True" to read_nnet, Marabou adjusts the parameters of the first and last layers of the
    network to incorporate the normalization.
    As a result, properties can be defined in the original input/output spaces without any manual normalization.
    """
    filename = "acasxu/ACASXU_experimental_v2a_1.nnet"
    testInputs = [
        [1000.0, 0.0, -1.5, 100.0, 100.0],
        [10000.0, -3.0, -1.5, 300.0, 300.0],
        [5000.0, -3.0, 0.0, 300.0, 600.0]
    ]
    testOutputs = [
        [177.87553729, 173.75796115, 193.05920806, 153.07876146, 195.00495022],
        [-0.55188079, 0.46863711, 0.44250383, 0.44151988, 0.43959133],
        [29.9190734, 27.2386958, 45.02497222, 14.5610455, 46.86448056]
    ]
    network = evaluateFile(filename, testInputs, testOutputs, normalize = True)
```



Katz, G., Huang, D. A., Ibeling, D., Julian, K., Lazarus, C., Lim, R., Shah, P., Thakoor, S., Wu, H., Zeljic, A., Dill, D. L., Kochenderfer, M. J., and Barrett, C. W. (2019). The Marabou framework for verification and analysis of deep neural networks. In CAV 2019

Verification framework: ERAN



```
1 [12000, 62000]
2 [0.7, 3.141592][-3.141592, -0.7]
3 [-3.141592, -3.136592]
4 [100, 1200]
5 [0, 600]
```

```
1 5
2 y0 min
```



Singh, G., Gehr, T., Püschel, M., and Vechev, M. T. (2019). An abstract domain for certifying neural networks. *PACMPL*, 3(POPL):41:1–41:30.

Verification property language: VNNLIB



```
28  (assert (or
29      (and (<= X_0 0.700434925) (>= X_0 -0.129289109)
30          (<= X_1 0.499999896) (>= X_1 0.11140846)
31          (<= X_2 -0.499204121) (|>= X_2 -0.499999896)
32          (<= X_3 0.5) (>= X_3 -0.5)
33          (<= X_4 0.5) (>= X_4 -0.5))
34      (and (<= X_0 0.700434925) (>= X_0 -0.129289109)
35          (<= X_1 -0.11140846) (>= X_1 -0.499999896)
36          (<= X_2 -0.499204121) (>= X_2 -0.499999896)
37          (<= X_3 0.5) (>= X_3 -0.5)
38          (<= X_4 0.5) (>= X_4 -0.5)))
39  ))
40
41 ; unsafe if coc is not minimal
42 (assert (or
43     (and (<= Y_1 Y_0))
44     (and (<= Y_2 Y_0))
45     (and (<= Y_3 Y_0))
46     (and (<= Y_4 Y_0)))
47  ))
48
```

Recap: What are the problems from the PL perspective?



Recap: What are the problems from the PL perspective?



- I^O* Interoperability – properties are not portable between training/counter-example search/ verification.

Recap: What are the problems from the PL perspective?



- I^O Interoperability – properties are not portable between training/counter-example search/ verification.
- I^P Interpretability – code is not easy to understand.

Recap: What are the problems from the PL perspective?



- I^O Interoperability – properties are not portable between training/counter-example search/ verification.
- I^P Interpretability – code is not easy to understand.
- I^I Integration – properties of networks cannot be linked to larger control system properties.

Recap: What are the problems from the PL perspective?

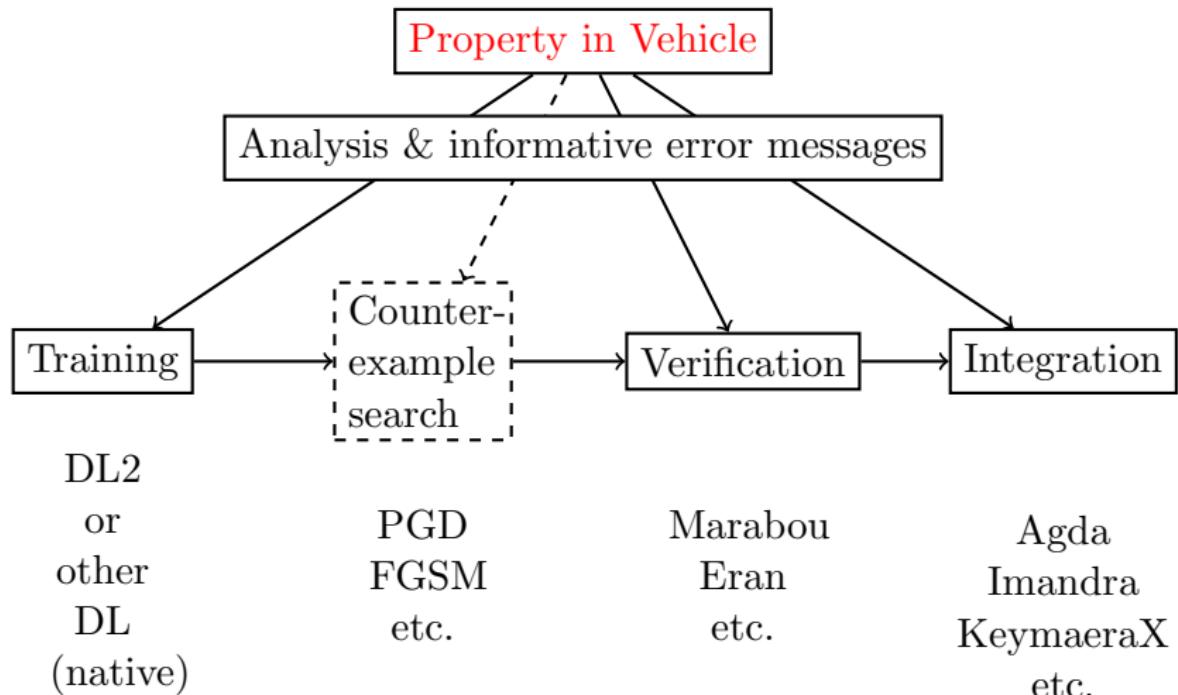


- I^O Interoperability – properties are not portable between training/counter-example search/ verification.
- I^P Interpretability – code is not easy to understand.
- I^I Integration – properties of networks cannot be linked to larger control system properties.
- E^G Embedding gap – little support for translation between problem space (as in original spec) and input space (at neural network level).

Vehicle is designed to address all of these problems

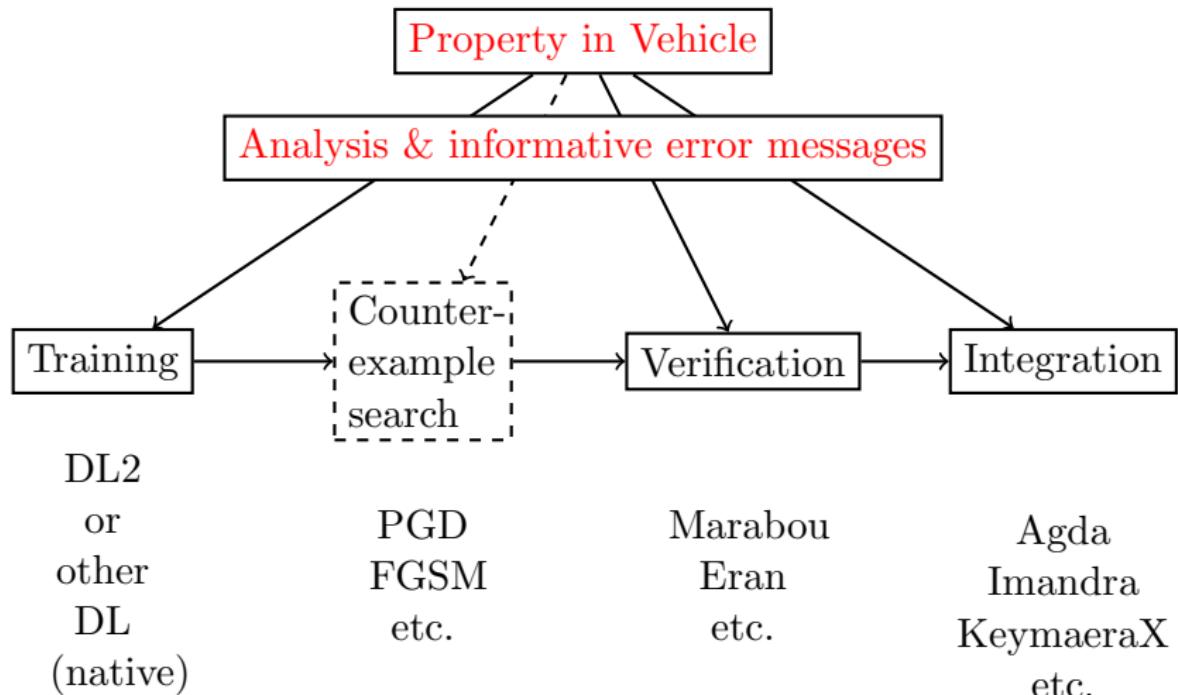
Vehicle ...

is a domain-specific functional language for writing high-level property specifications for neural networks



Vehicle ...

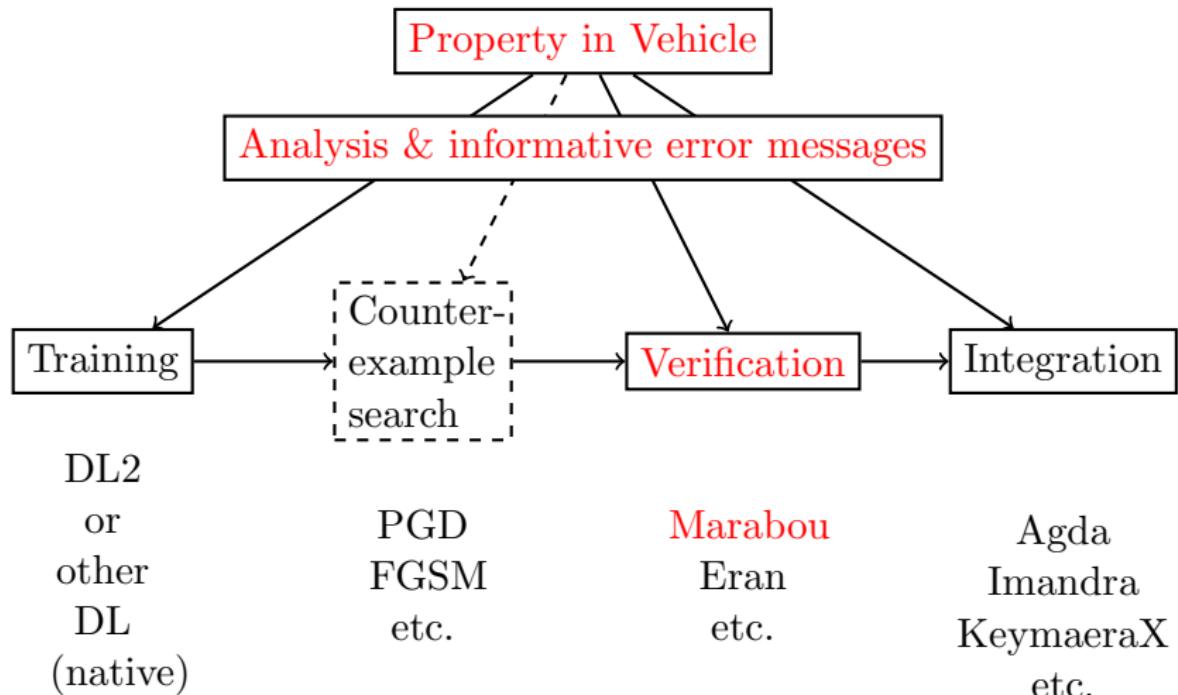
is a domain-specific functional language for writing high-level property specifications for neural networks



Vehicle ...

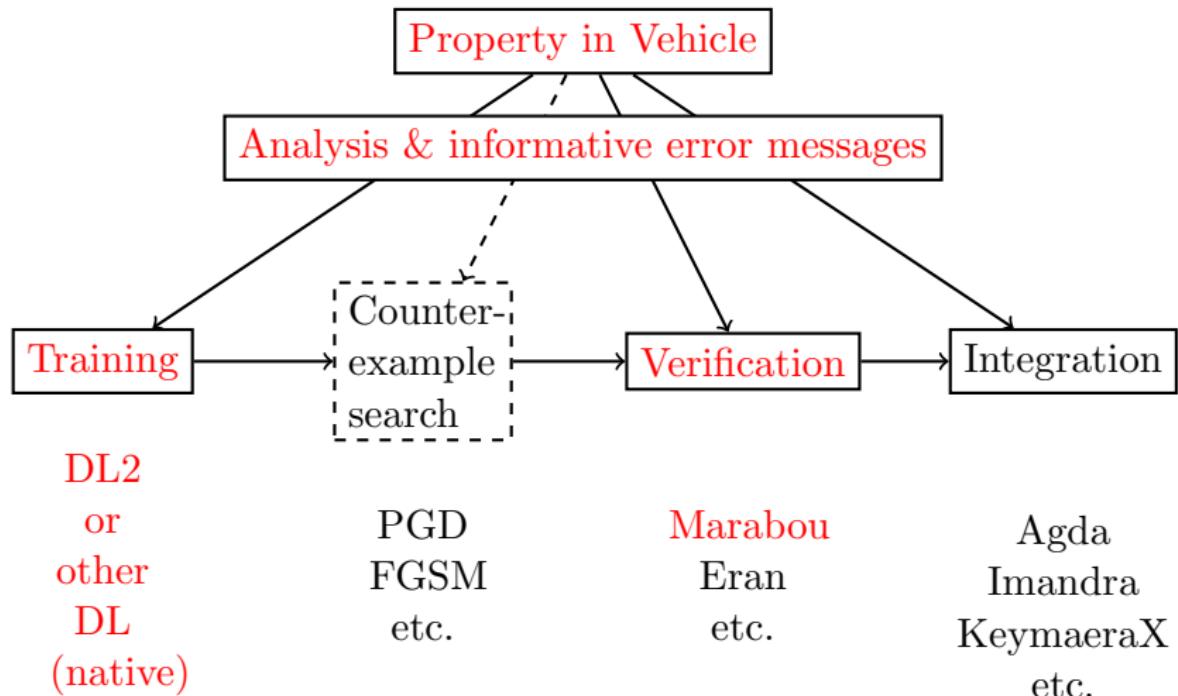


is a domain-specific functional language for writing high-level property specifications for neural networks



Vehicle ...

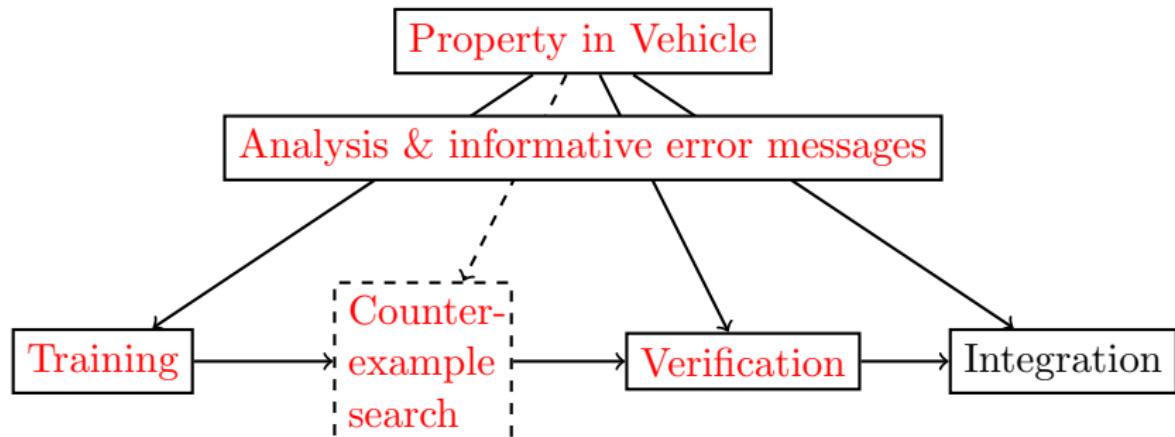
is a domain-specific functional language for writing high-level property specifications for neural networks



Vehicle ...



is a domain-specific functional language for writing high-level property specifications for neural networks



DL2

or
other
DL
(native)

PGD
FGSM
etc.

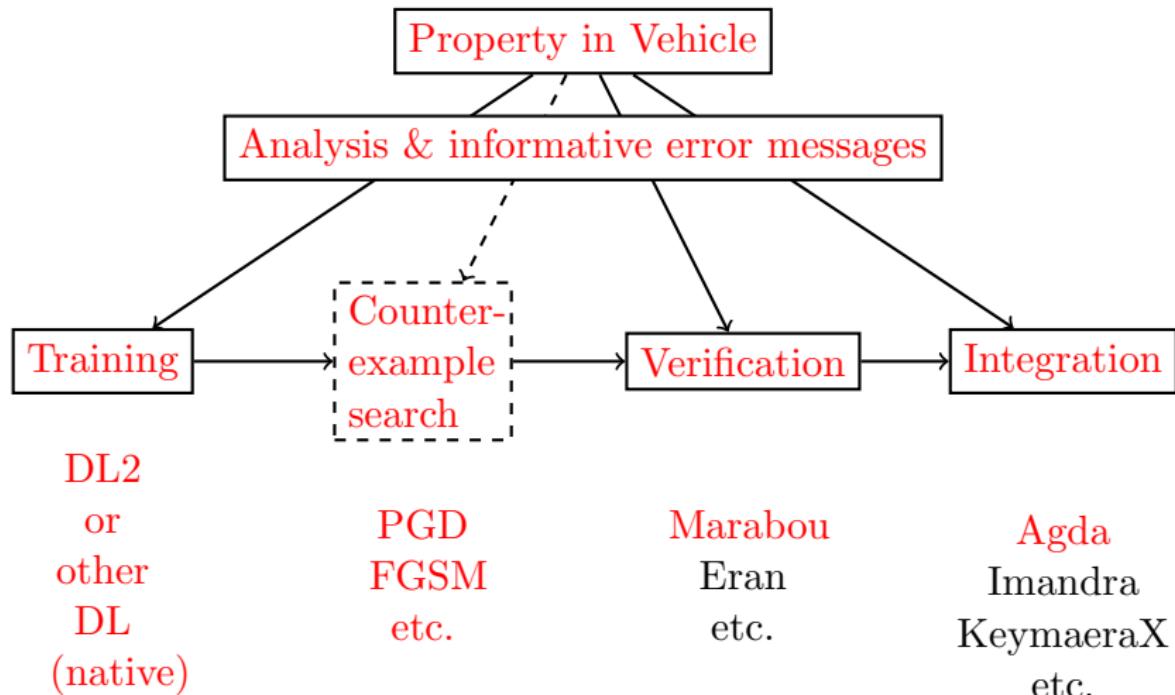
Marabou
Eran
etc.

Agda
Imandra
KeymaeraX
etc.

Vehicle ...



is a domain-specific functional language for writing
high-level property specifications for neural networks





Other Similar APIs

- ▶ Socrates [in Python]: Given a spec and a network (in JSON), calls different NN verifiers.
 - ◀ L. H. Pham, J. Li, and J. Sun. 2020. SOCRATES: Towards a Unified Platform for Neural Network Verification. CoRR abs/2007.11206.

Left unresolved: I^O, I^P, I^S, E^G



Other Similar APIs

- ▶ Socrates [in Python]: Given a spec and a network (in JSON), calls different NN verifiers.
 - L. H. Pham, J. Li, and J. Sun. 2020. SOCRATES: Towards a Unified Platform for Neural Network Verification. CoRR abs/2007.11206.
- Left unresolved: I^O, I^P, I^f, E^G
- ▶ NeVer 2.0 [in Python]: added training, pruning and quantization to this functionality.
 - D. Guidotti, L. Pulina, and A. Tacchella. 2020. NeVer 2.0: Learning, Verification and Repair of Deep Neural Networks. CoRR abs/2011.09933.
- Resolved: I^O (partially). Left untesolved: I^P, I^f, E^G



Other Similar APIs

- ▶ Socrates [in Python]: Given a spec and a network (in JSON), calls different NN verifiers.
 - L. H. Pham, J. Li, and J. Sun. 2020. SOCRATES: Towards a Unified Platform for Neural Network Verification. CoRR abs/2007.11206.
Left unresolved: I^O, I^P, I^f, E^G
- ▶ NeVer 2.0 [in Python]: added training, pruning and quantization to this functionality.
 - D. Guidotti, L. Pulina, and A. Tacchella. 2020. NeVer 2.0: Learning, Verification and Repair of Deep Neural Networks. CoRR abs/2011.09933.
Resolved: I^O (partially). Left untesolved: I^P, I^f, E^G
- ▶ CoCoNet [in Python]: NN format converter with GUI
 - D. Guidotti, A. Tacchella, L. Pulina, S. Demarchi 2023.
<http://neuralverification.org/>
Resolved: I^P (partially). Left untesolved: I^O, I^f, E^G



Other Similar APIs

- ▶ Socrates [in Python]: Given a spec and a network (in JSON), calls different NN verifiers.
 - ❑ L. H. Pham, J. Li, and J. Sun. 2020. SOCRATES: Towards a Unified Platform for Neural Network Verification. CoRR abs/2007.11206.
Left unresolved: I^O, I^P, I^f, E^G
 - ▶ NeVer 2.0 [in Python]: added training, pruning and quantization to this functionality.
 - ❑ D. Guidotti, L. Pulina, and A. Tacchella. 2020. NeVer 2.0: Learning, Verification and Repair of Deep Neural Networks. CoRR abs/2011.09933.
- Resolved: I^O (partially). Left untesolved: I^P, I^f, E^G
- ▶ CoCoNet [in Python]: NN format converter with GUI
 - ❑ D. Guidotti, A. Tacchella, L. Pulina, S. Demarchi 2023.
<http://neuralverification.org/>
- Resolved: I^P (partially). Left untesolved: I^O, I^f, E^G
- ▶ Caisar [in OCAML] – general specification language and connection to several NN Verifiers
 - ❑ J. Girard-Satabin, M. Alberti, F. Bobot, Z. Chihani, and A. Lemesle. 2022. CAISAR: A platform for Characterizing Artificial Intelligence Safety and Robustness. In AISafety.
- Resolved: I^P, I^f . Left unresolved: I^O, E^G

Table of Contents



Neural Network Verification: overview of the new domain

The lifecycle of neural network verification

Challenges and Languages

Vehicle's Role and Purpose of this Tutorial

Vehicle's Aim...



... is to resolve the problems I^O , I^P , I^f , E^G

Vehicle's Aim...



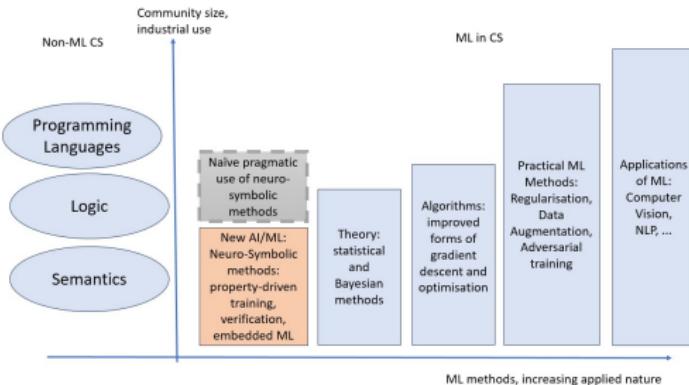
... is to resolve the problems I^O , I^P , I^f , E^G

... and support community's effort towards resolution of the
“Grand Challenges”

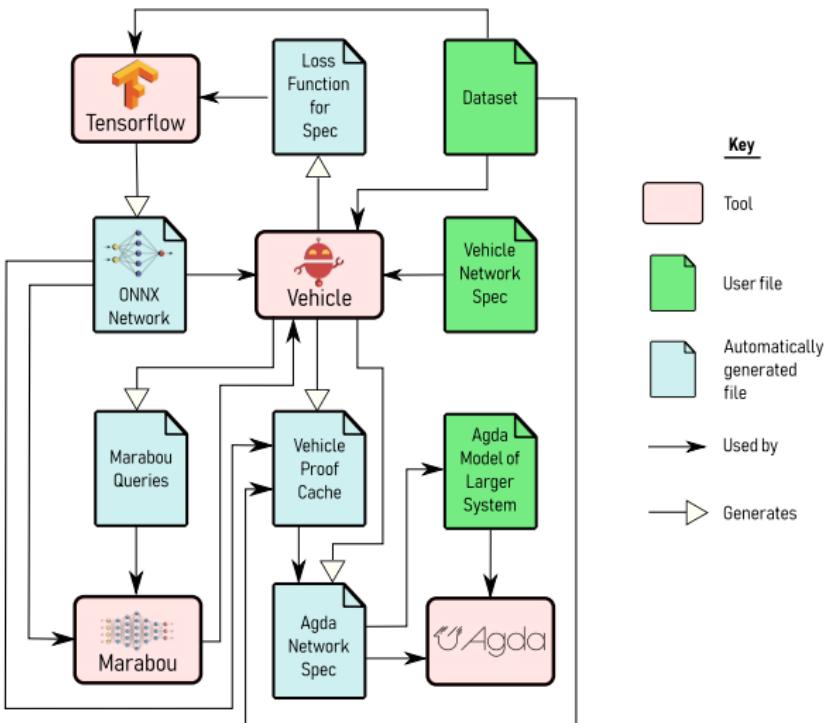
“Grand Challenges” & Vehicle



- ▶ Theory: finding appropriate verification properties
- ▶ Solvers: undecidability of non-linear real arithmetic and scalability of neural network verifiers
- ▶ ML: understanding and integrating property-driven training
- ▶ Programming: finding the right languages to support these developments
- ▶ Complex systems: integration of neural net verification into complex systems



Vehicle Architecture



Sources



-  M. Daggitt, R. Atkey, W. Kokke, E. Komendantskaya, L. Arnaboldi: Compiling Higher-Order Specifications to SMT Solvers: How to Deal with Rejection Constructively. CPP 2023
-  N. Slusarz, E. Komendantskaya, M. Daggitt, R. Stewart, K. Stark: Logic of Differentiable Logics: Towards a Uniform Semantics of DL. LPAR 2023.
-  Matthew L. Daggitt, Wen Kokke, Robert Atkey, Luca Arnaboldi, Ekaterina Komendantskaya: Vehicle: Interfacing Neural Network Verifiers with Interactive Theorem Provers. FOMLAS 2022
-  Vehicle Team: The Vehicle language: <https://github.com/vehicle-lang> 2023.
-  M.Daggitt and W.Kokke: Vehicle User Manual.
<https://vehicle-lang.readthedocs.io> 2023.
-  The Vehicle team: Vehicle Tutorial <https://vehicle-lang.github.io>. 2023.
Tutorial code repository
<https://github.com/vehicle-lang/vehicle-tutorial>.

Purpose of this Tutorial...



- ▶ Introduce **Vehicle** specification language at the user level
- ▶ Discuss challenges in NN verification ("grand" and technical)
- ▶ Gather feedback and obtain community support

Thanks

... to Marabou team and FOMLAS organisers for the continuing support!

Plan for the rest of this tutorial



- ▶ Before coffee break:
 - ▶ Brief introduction to **Vehicle** specification language
 - ▶ **Exercise session:** write and verify a spec (with possibility to extend over the break)
Tutorial pages: <https://vehicle-lang.github.io>
 - ▶ Join tutorial Slack channel via FOMLAS'23 page, to ask questions
- ▶ After the break:
 - ▶ Demo of property-driven training in Vehicle
 - ▶ Demo of large system integration in Vehicle
- ▶ After this tutorial – Natalia Slusarz: theory behind property-driven training