Assured Autonomy for Systems with Neural Network Components

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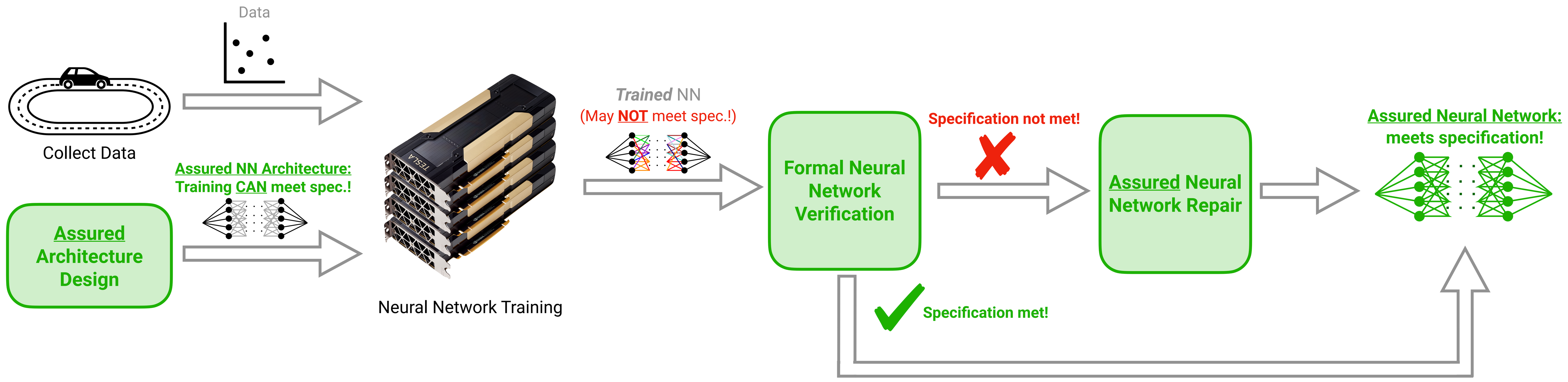
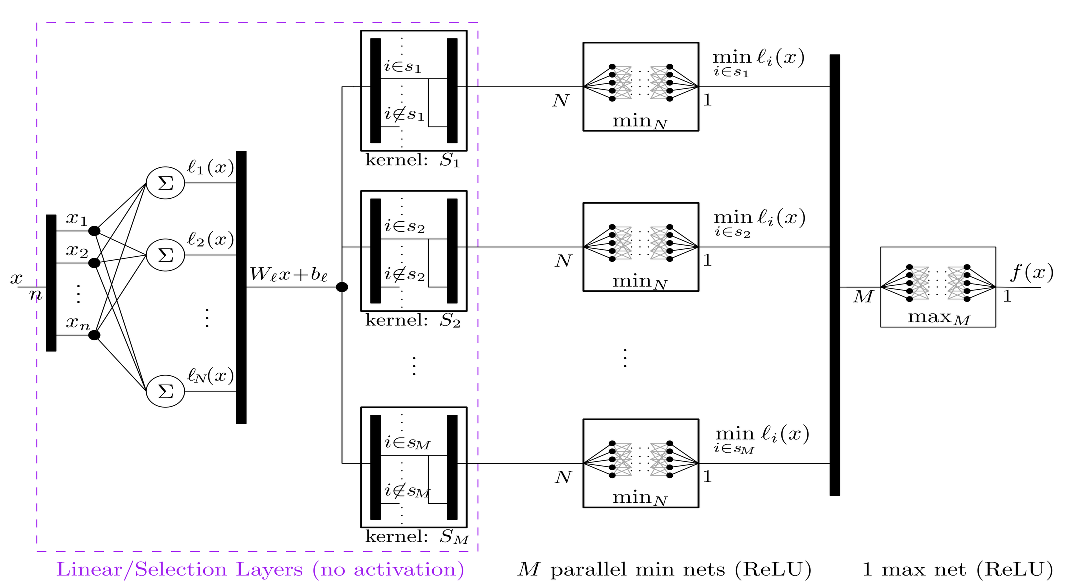
Assured Autonomy Neural Network (NN) Design Pipeline

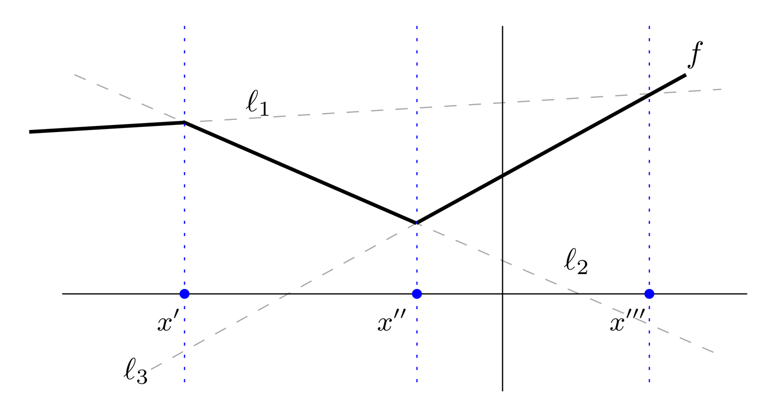
Pipeline of design components to enforce assurances before and after training: **assured architectures**; **formal verification**; and **assured repair**.



Key Idea: *Semantic* NN Architecture — Two-Level Lattice (TLL)

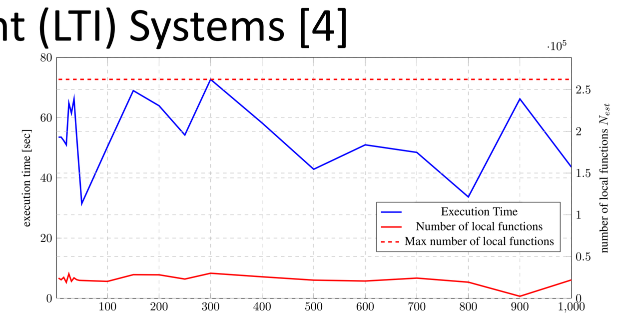


- Based on **Two-Level Lattice (TLL representation** for Continuous, Piecewise Affine (CPWA) functions [10]
- Rectified Linear Unit (ReLU) TLL NNs [4]:
  - Two "levels" of lattice operations: **min** and **max** operations via ReLUs **(all nonlinear neurons in these layers!)**
  - **Local affine functions appear directly as neuron weights** (first layer) [4] (e.g. ℓ_1, ℓ_2 and ℓ_3 in the figure to the right)
  - **Activation region** of local affine functions determined by "selection layer"
- Semantic NN Architecture: **specific neuron weights ⟷ specific properties of NN function**



Assured TLL NN Architectures

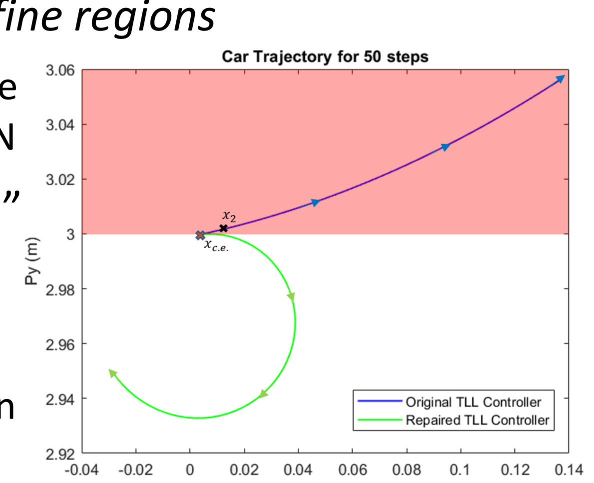
- **Assure that NN training *CAN* be successful**
- Assured NN architectures for Linear-Time Invariant (LTI) Systems [4]
  - Size TLL NN architecture based on Model-Predictive Control
  - Explicit MPC controller **not** required: **fast algorithm** (**assured** architecture in seconds not days like NAS)



- Assured NN architectures for Nonlinear Systems [6,8]
  - Assure more general specifications, too: **bisimulation**
  - **Abstract Disturbance Simulation** → unify/extend robust and disturbance bisimulation
  - **Algorithmic translation of (known) Lipschitz-continuous controller to TLL** [6]

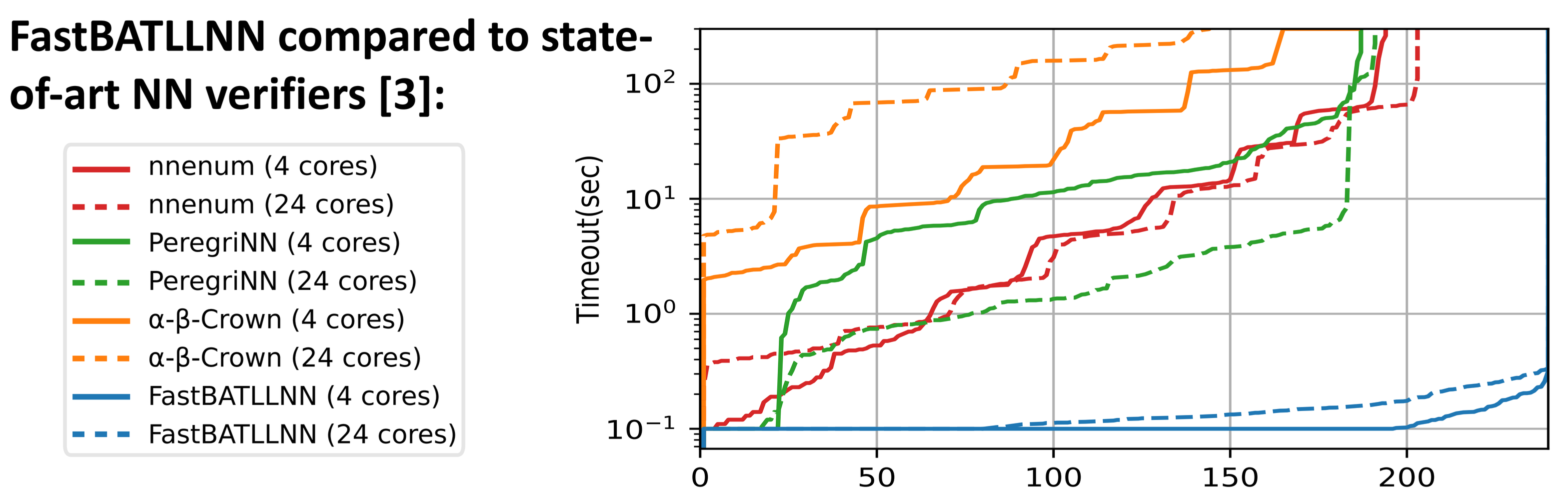
Assured TLL NN Repair

- **Repair counterexample from formal verification: no assurance → assurance**
- Also: repair c.e. while assuring existing safe behavior is retained [1]
- Repair problem is hard: *one neuron affects many affine regions*
  - Change one neuron to repair c.e. → behavior elsewhere in state space is affected → undo original safety of NN
- Solution: TLL ***semantics*** separate "local" and "global" concerns (local linear functions/selector layer) [1]
  - Input-affine dynamics/one-step counterexample [1]:
    - Alternate between Local & Global convex optimization problems

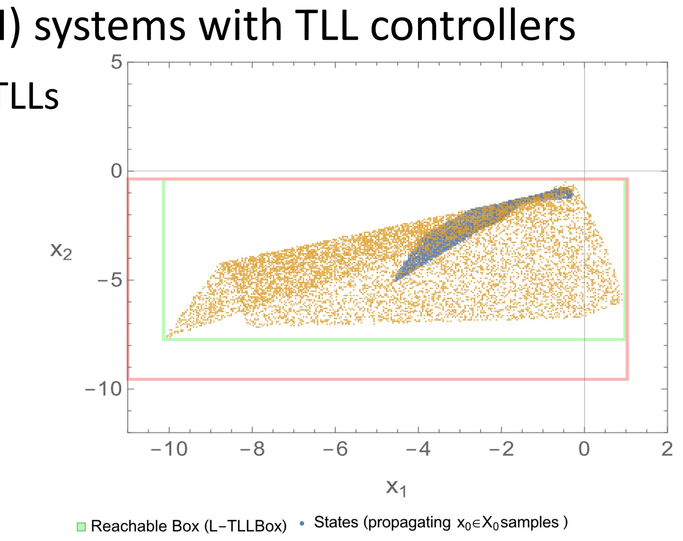


Formal TLL NN Verification

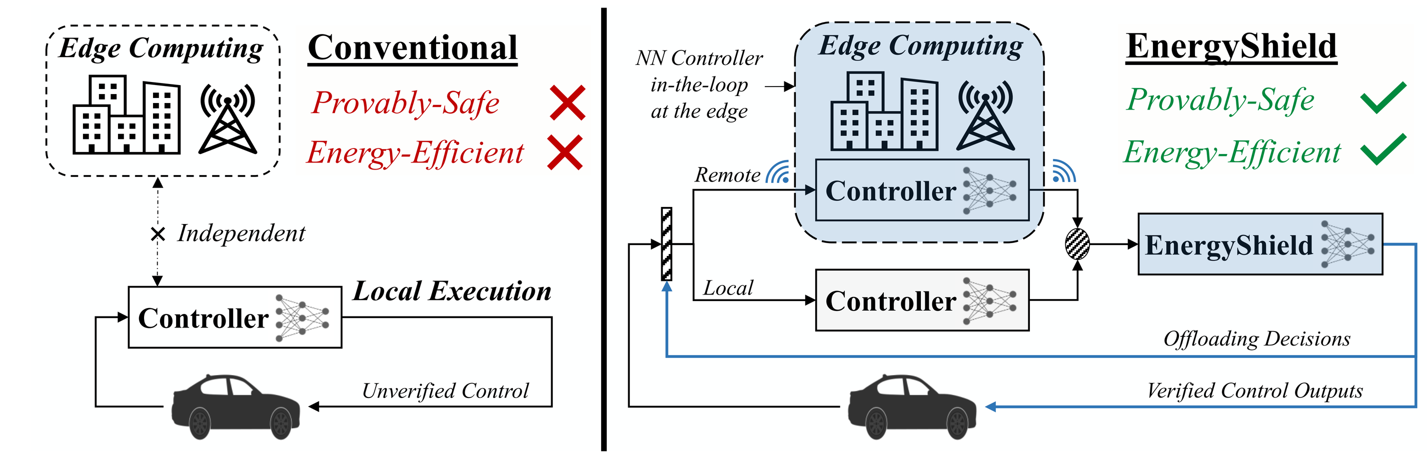
- Fast **polynomial** complexity algorithms for TLL Verification (in # neurons) [5]
  - Restricted architectures → faster verification [5]
- Fast Box Analysis of Two Level Lattice NNs: **FastBATLLNN** [3]
  - Restricted, "Box-like" (hypercube) output constraints → even faster [3]
  - Polynomial complexity (in # neurons)
  - Exploit constraints and min/max semantics
- **FastBATLLNN compared to state-of-art NN verifiers [3]:**



- Fast reachability for Linear Time-Invariant (LTI) systems with TLL controllers
  - One-step exact LTI reachability **polynomial** for TLLs (exponential for DNNs) [7]
  - **L-TLLBox** [7]: faster speed using bounding box propagation (leverage **FastBATLLNN**)
- Example bounding box after T=3 steps [7]
  - **L-TLLBox (green): 25 seconds**
  - **NNV (red): 139,000 seconds**



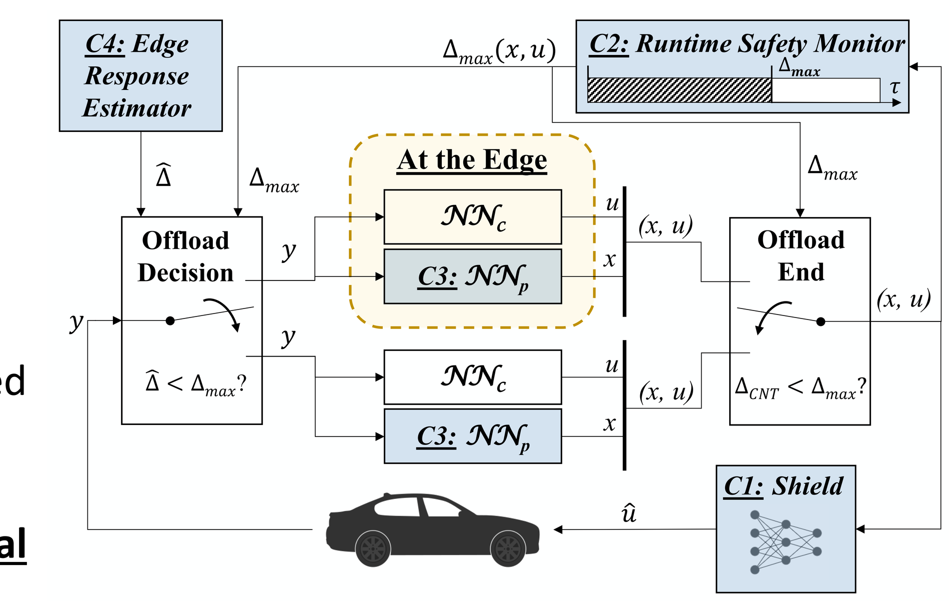
Safe Vehicle-to-Edge NN Offloading



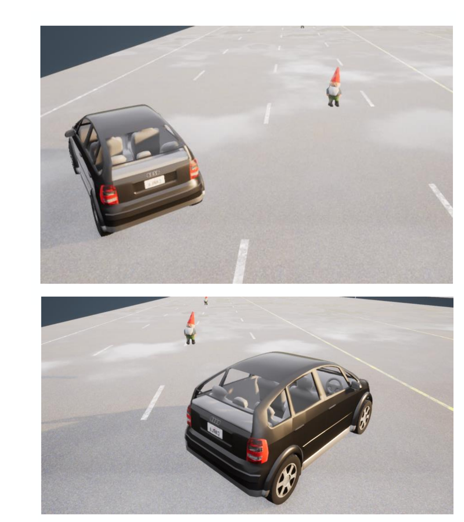
- Energy used by **NN hardware reduces Electric Vehicle range by up to 15% !**

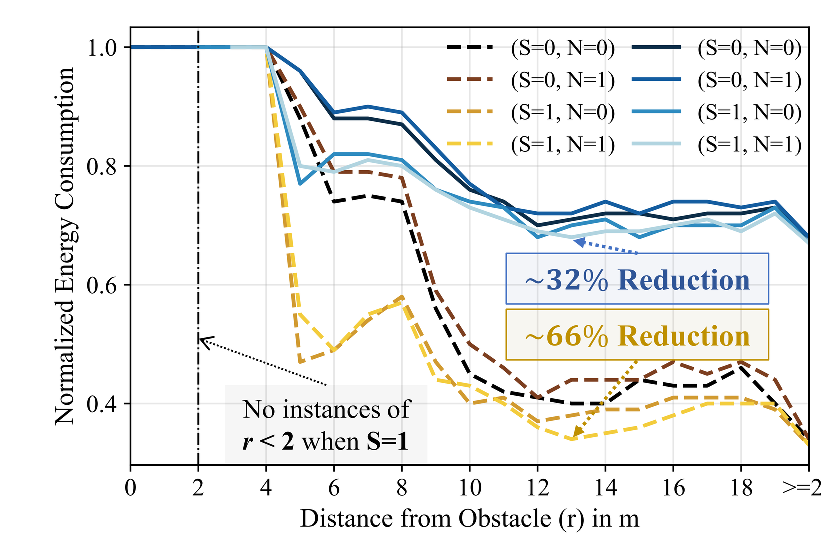
Controller "Shield": Runtime safety monitor

- Use controller shield to **bound safe edge response times** [9]
- Controller shield **assures** safety after receiving response [2]
- On-vehicle computation used as fallback
- **Energy use (and hence simplicity) of shield is critical**



EnergyShield [9]: Safety and Energy Savings





- State dependent energy savings: **more energy saved when "safer"**!

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