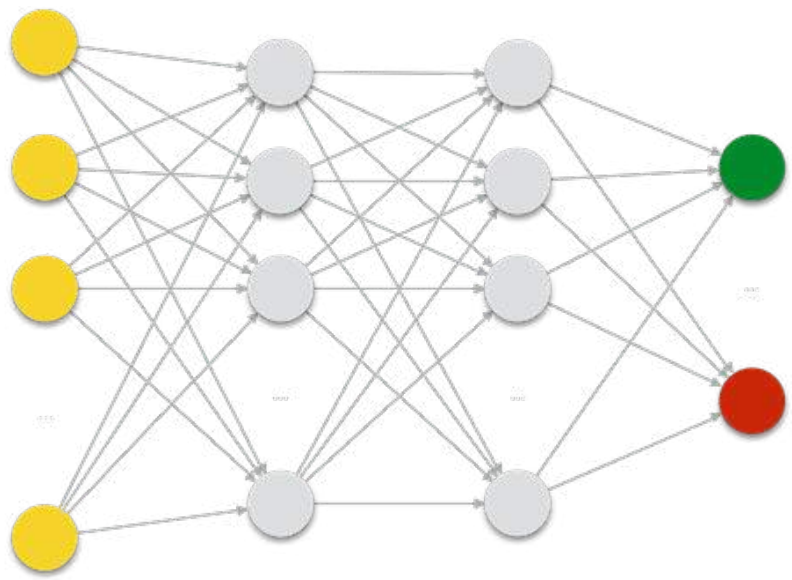
Formal Verification of Machine Learning

MPRI 2-6: Abstract Interpretation, Application to Verification and Static Analysis



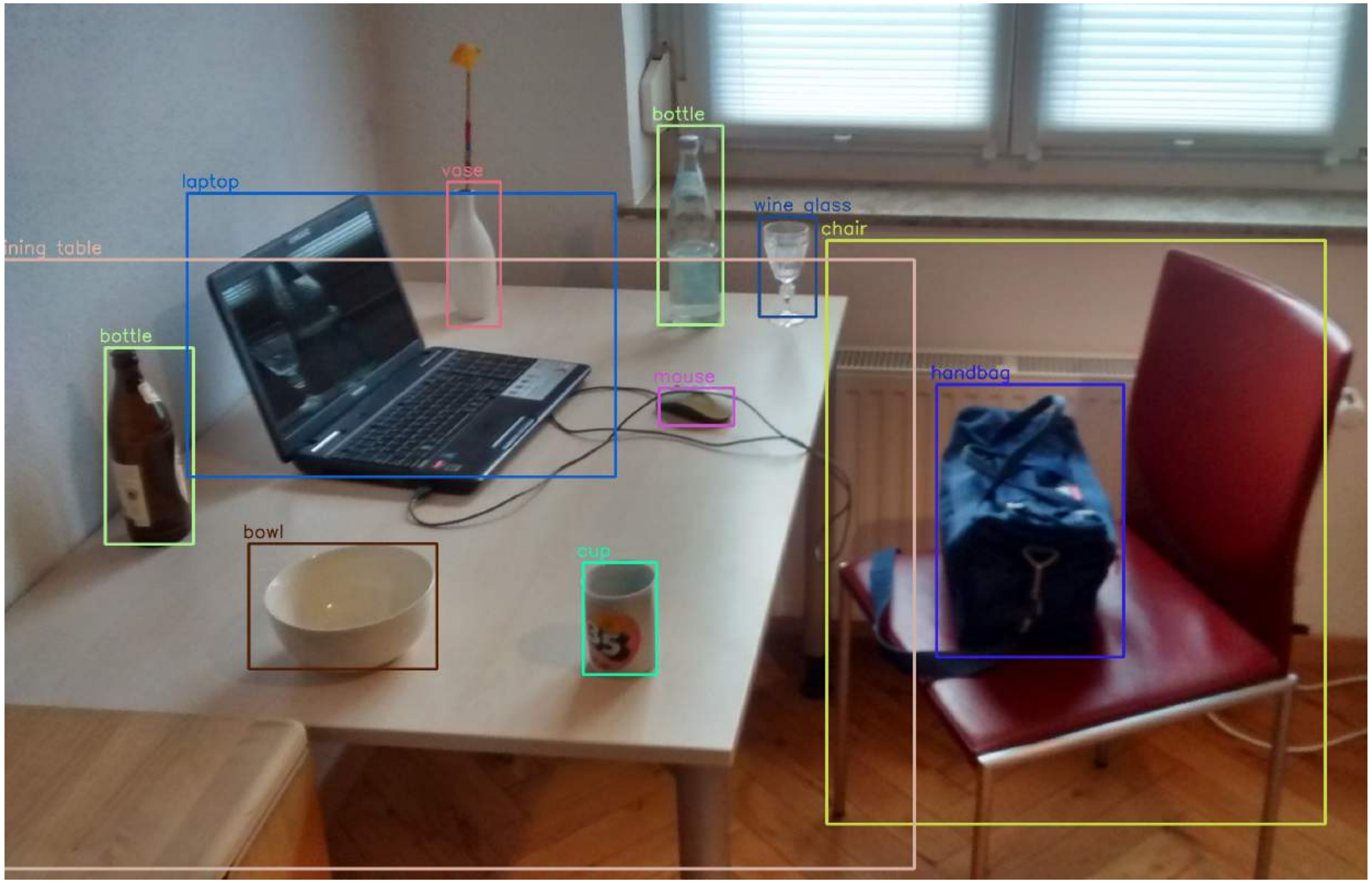
Caterina Urban

November 14th, 2022

Year 2022-2023

Machine Learning Revolution

Computer software able to efficiently and **autonomously perform tasks** that are difficult or even *impossible* to design using explicit programming



Examples: object recognition, image classification, speech recognition, etc.

ML in Safety-Critical Applications

Enables **new functions that could not be envisioned before**

Self-Driving Cars

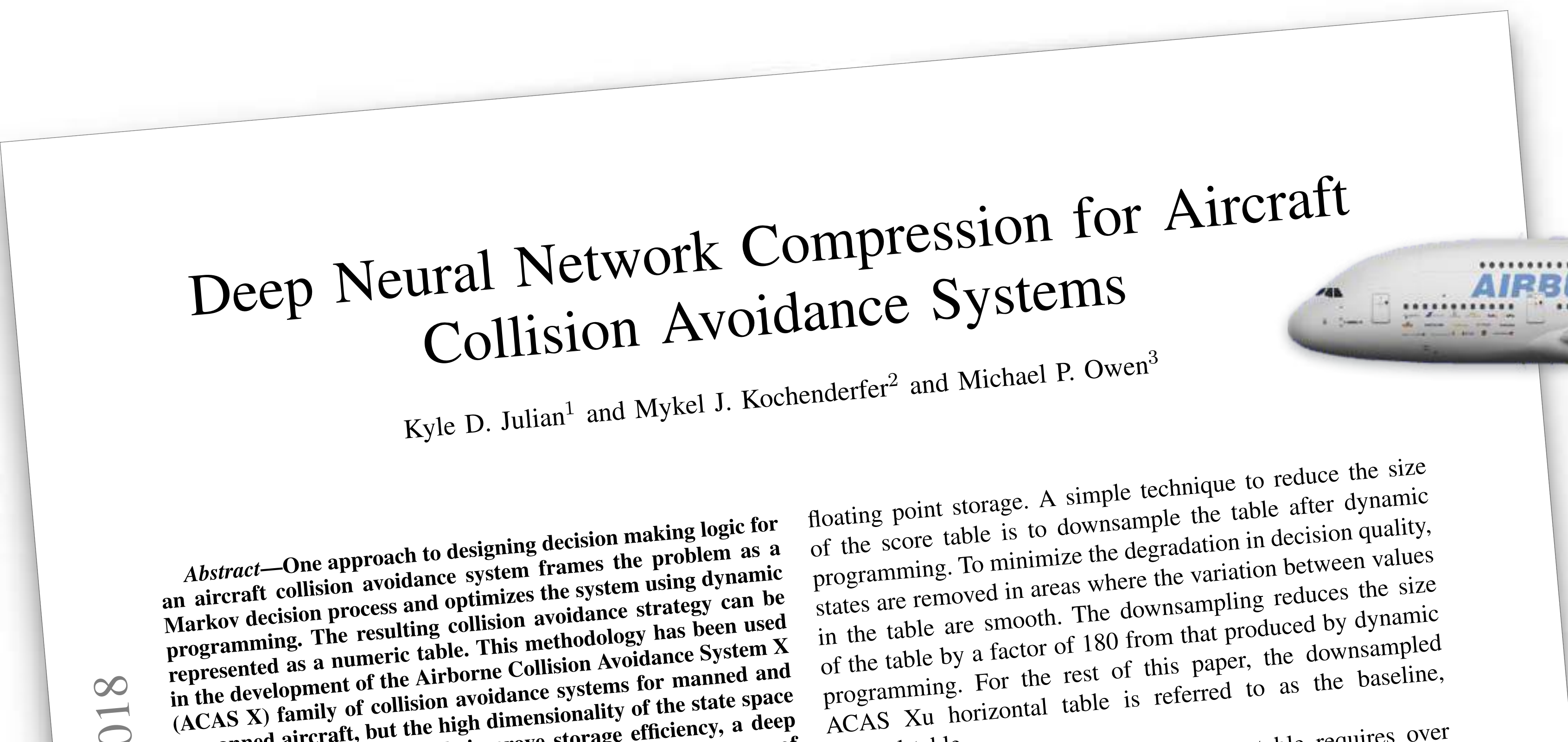
Image-Based Taxiing, Takeoff, Landing

Aircraft Voice Control

ML in Safety-Critical Applications

Approximates complex systems and **automates decision-making**

Diagnosis and Drug Discovery



Deep Neural Network Compression for Aircraft Collision Avoidance Systems

Kyle D. Julian[1] and Mykel J. Kochenderfer[2] and Michael P. Owen[3]

Abstract—One approach to designing decision making logic for an aircraft collision avoidance system frames the problem as a Markov decision process and optimizes the system using dynamic programming. The resulting collision avoidance strategy can be represented as a numeric table. This methodology has been used in the development of the Airborne Collision Avoidance System X (ACAS X) family of collision avoidance systems for manned and unmanned aircraft, but the high dimensionality of the state space

floating point storage. A simple technique to reduce the size of the score table is to downsample the table after dynamic programming. To minimize the degradation in decision quality, states are removed in areas where the variation between values in the table are smooth. The downsampling reduces the size of the table by a factor of 180 from that produced by dynamic programming. For the rest of this paper, the downsampled ACAS Xu horizontal table is referred to as the baseline, original table.

Aircraft Collision Avoidance

ML in Safety-Critical Applications

[1] STAT+ [2]

IBM's Watson supercomputer recommended 'unsafe and incorrect' cancer treatments, internal documents show

By Casey Ross[3] @caseymross[4] *and* Ike Swetlitz

July 25, 2018

A self-driving Uber ran a red light last December, contrary to company claims

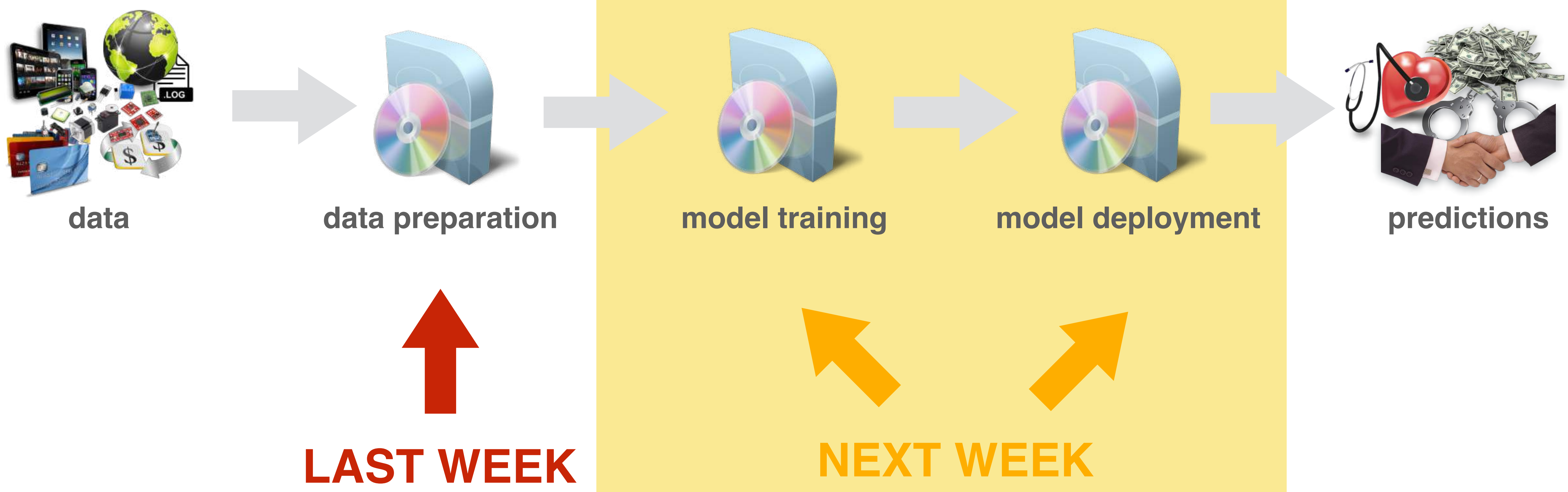
Internal documents reveal that the car was at fault

By Andrew Liptak | @AndrewLiptak | Feb 25, 2017, 11:08am EST

Feds Say Self-Driving Uber SUV Did Not Recognize Jaywalking Pedestrian In Fatal Crash

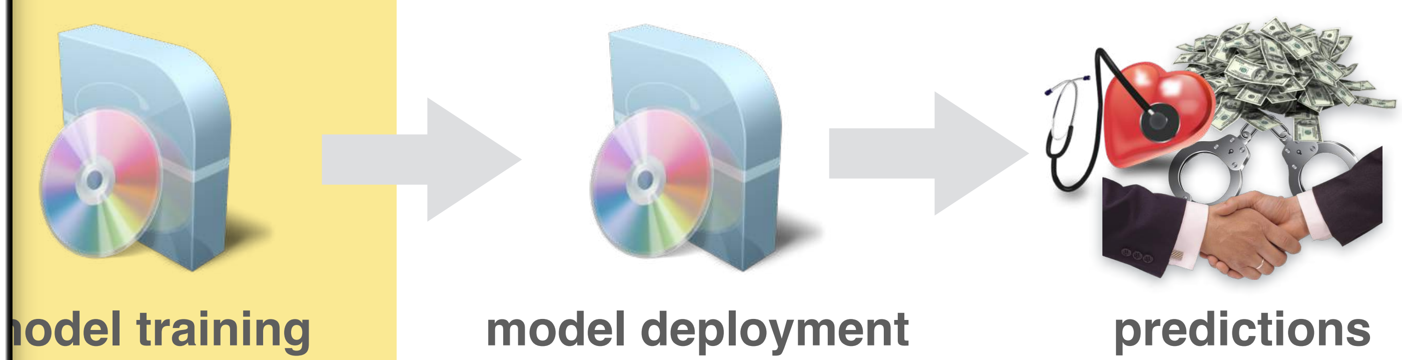
Richard Gonzales November 7, 201910:57 PM ET

Machine Learning Pipeline



Machine Learning Pipeline

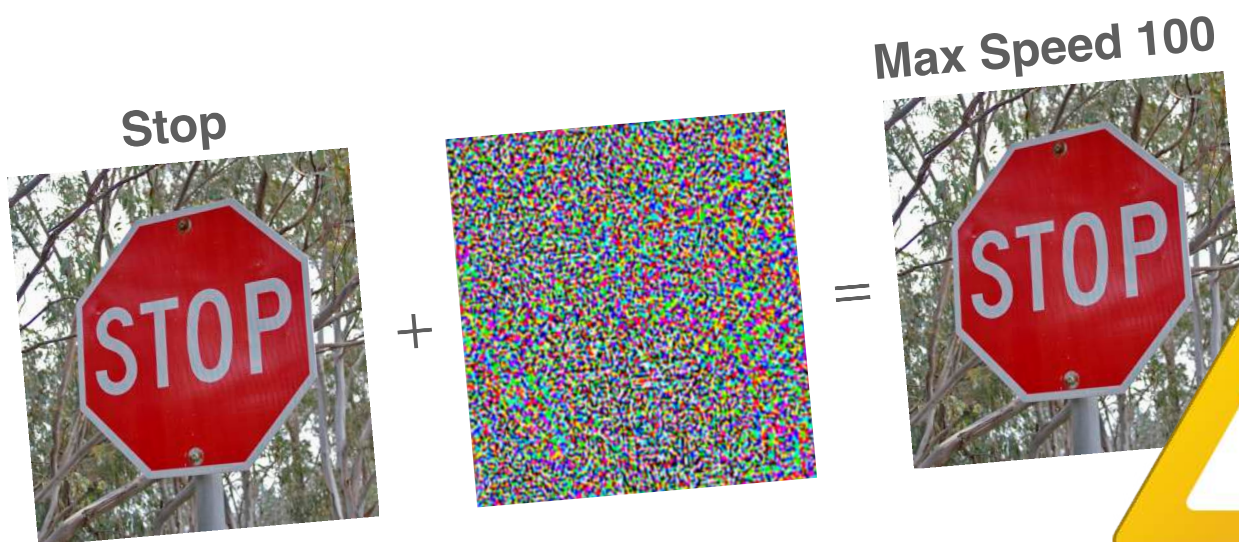
Model Training is **Highly Non-Deterministic**



no **predictability** and **traceability**

Machine Learning Pipeline

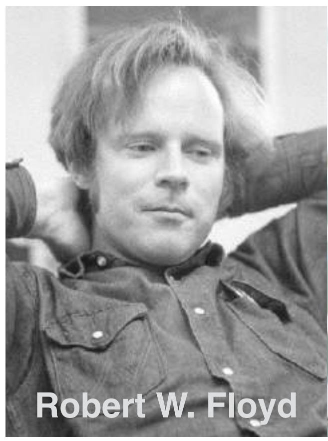
Models Only Give Probabilistic Guarantees



not sufficient for guaranteeing an acceptable failure rate under any circumstance

Formal Methods

Mathematical Guarantees of Safety



Deductive Verification

- extremely **expressive**
- **relies on the user** to guide the proof

Model Checking

- analysis of a **model** of the software
- **sound and complete**
  with respect to the model

Static Analysis

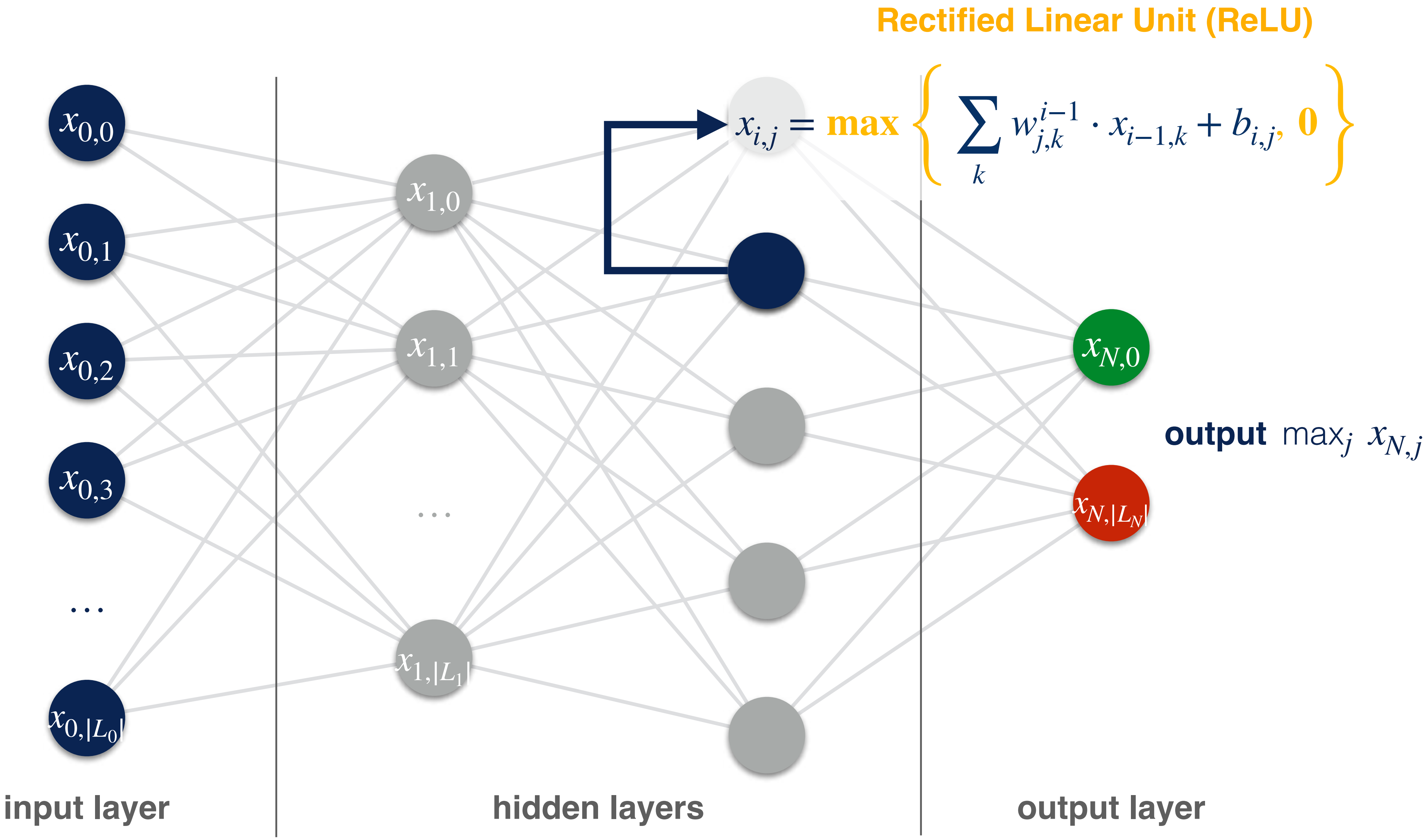
- analysis of the software
  at some level of **abstraction**
- fully **automatic** and **sound** by construction
- generally **not complete**

Formal Methods for Trained Models

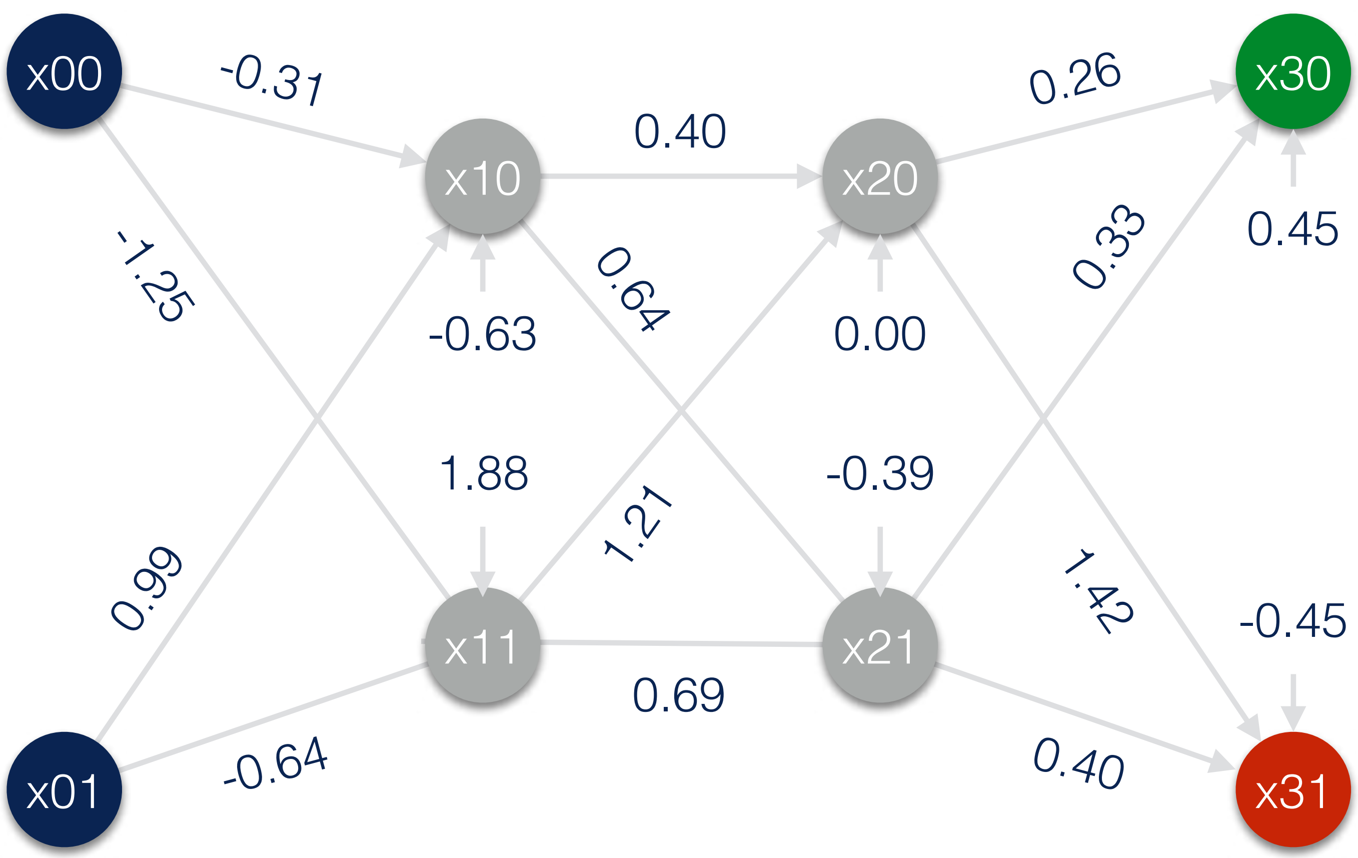
Neural Networks

Neural Networks

Feed-Forward **Fully-Connected** Neural Networks with **ReLU Activation Functions**

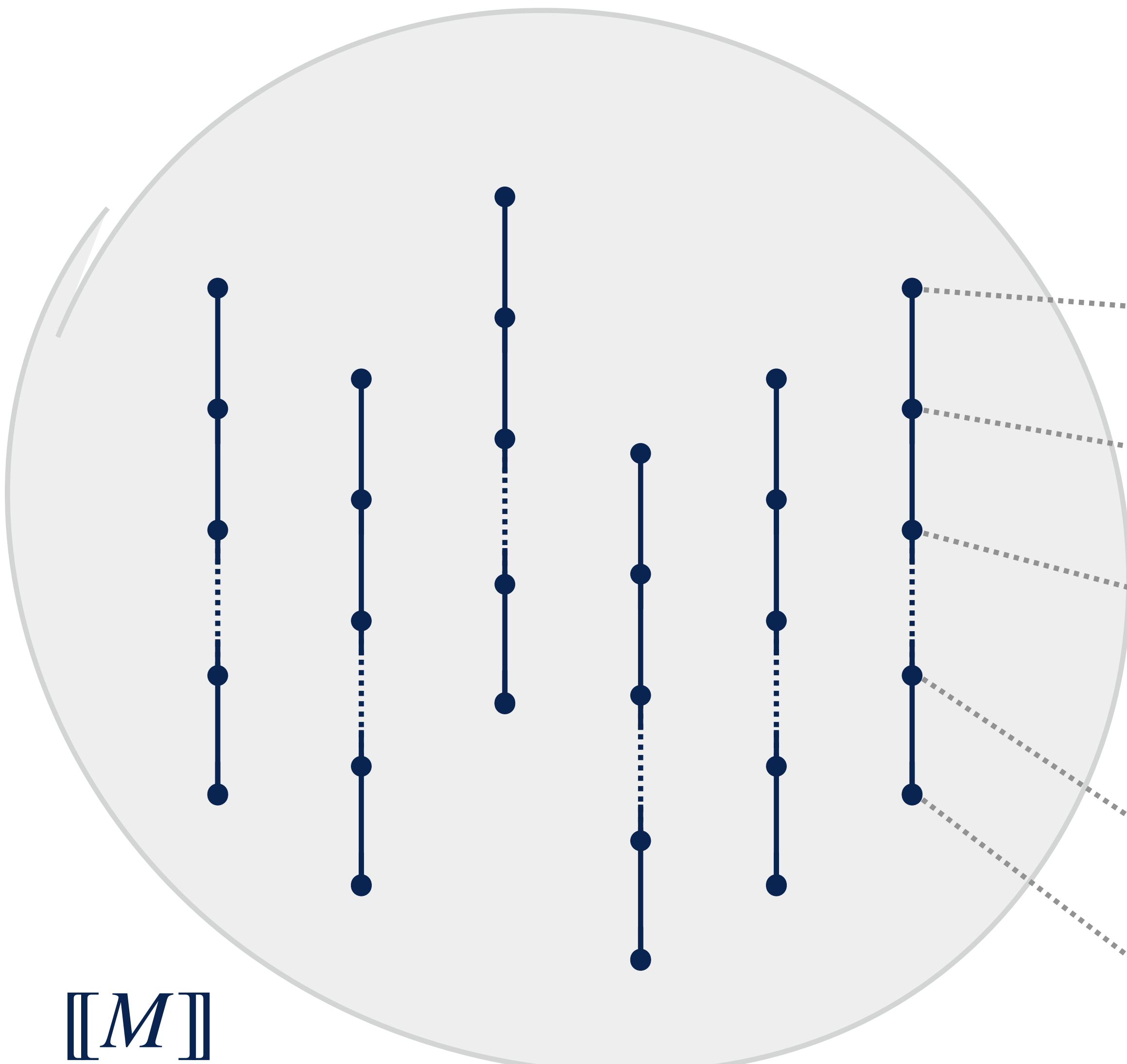


Feed-Forward Fully-Connected ReLU Networks as Programs




```
x00 = input()
x01 = input()

x10 = -0.31 * x00 + 0.99 * x01 + (-0.63)
x11 = -1.25 * x00 + (-0.64) * x01 + 1.88

x10 = 0 if x10 < 0 else x10
x11 = 0 if x11 < 0 else x11

x20 = 0.40 * x10 + 1.21 * x11 + 0.00
x21 = 0.64 * x10 + 0.69 * x11 + (-0.39)

x20 = 0 if x20 < 0 else x20
x21 = 0 if x21 < 0 else x21

x30 = 0.26 * x20 + 0.33 * x21 + 0.45
X31 = 1.42 * x20 + 0.40 * x21 + (-0.45)

return ‘ ’ if x31 < 30 else ‘ ’
```

Maximal Trace Semantics



$[\![M]\!]$

M

```
x00 = input()
x01 = input()

x10 = -0.31 * x00 + 0.99 * x01 + (-0.63)
x11 = -1.25 * x00 + (-0.64) * x01 + 1.88

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x30 = 0.26 * x20 + 0.33 * x21 + 0.45
X31 = 1.42 * x20 + 0.40 * x21 + (-0.45)

return ‘ ’ if x31 < 30 else ‘ ’
```
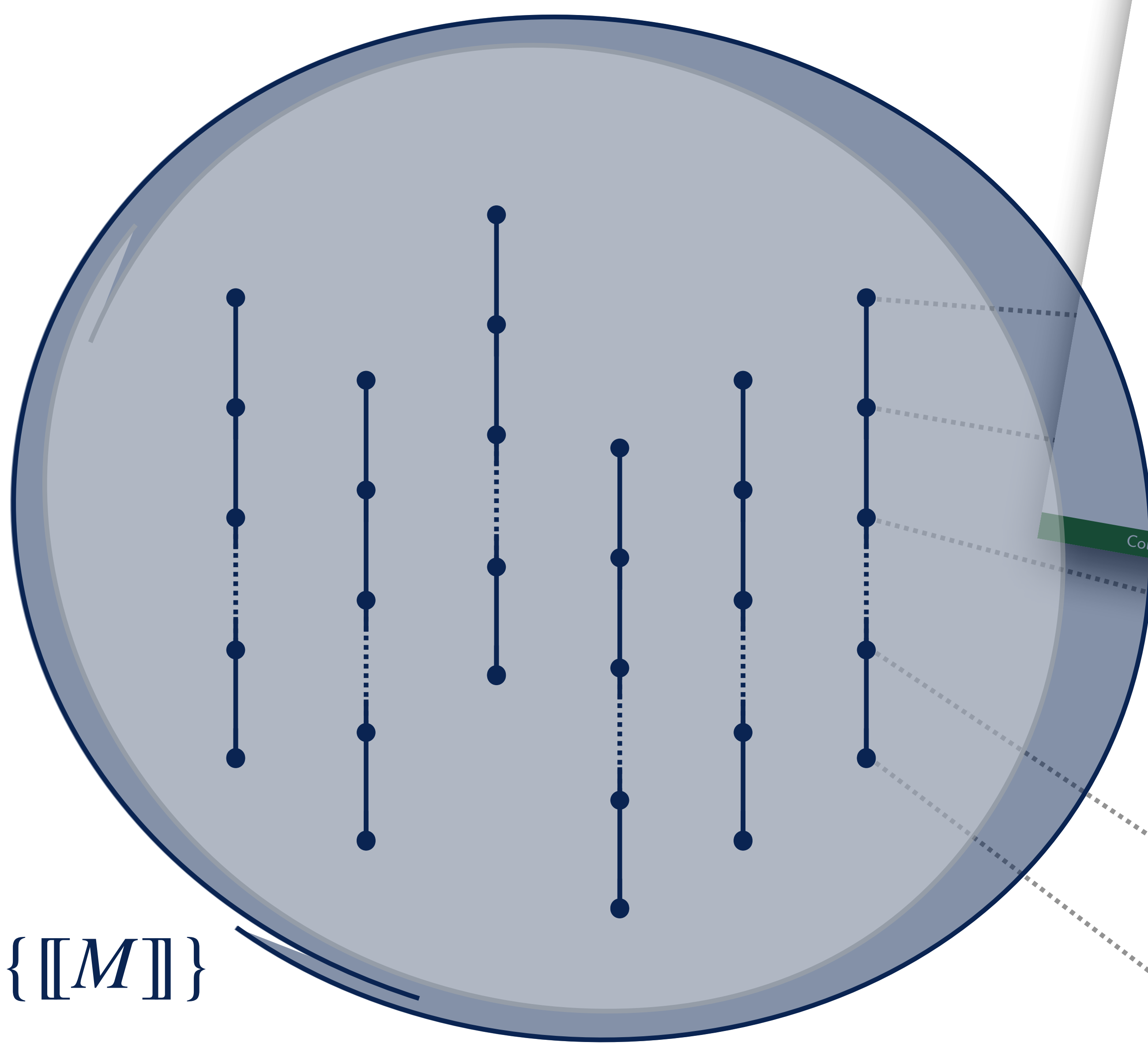
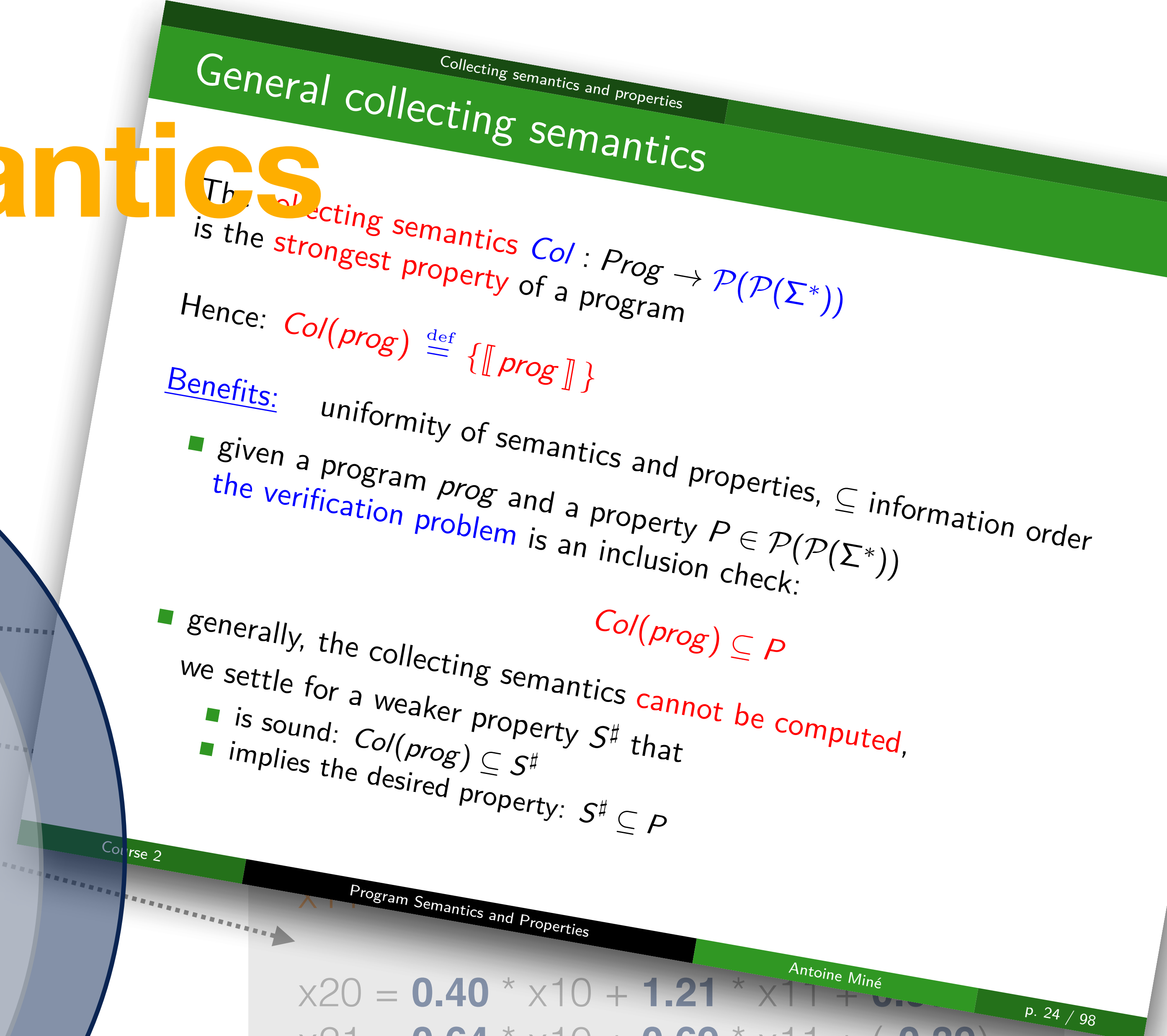

Neural Network Verification

Collecting Semantics





Collecting semantics and properties

General collecting semantics

The collecting semantics $Col : Prog \to \mathcal{P}(\mathcal{P}(\Sigma^*))$ is the strongest property of a program

Hence: $Col(prog) \stackrel{\text{def}}{=} \{[\![prog]\!]\}$

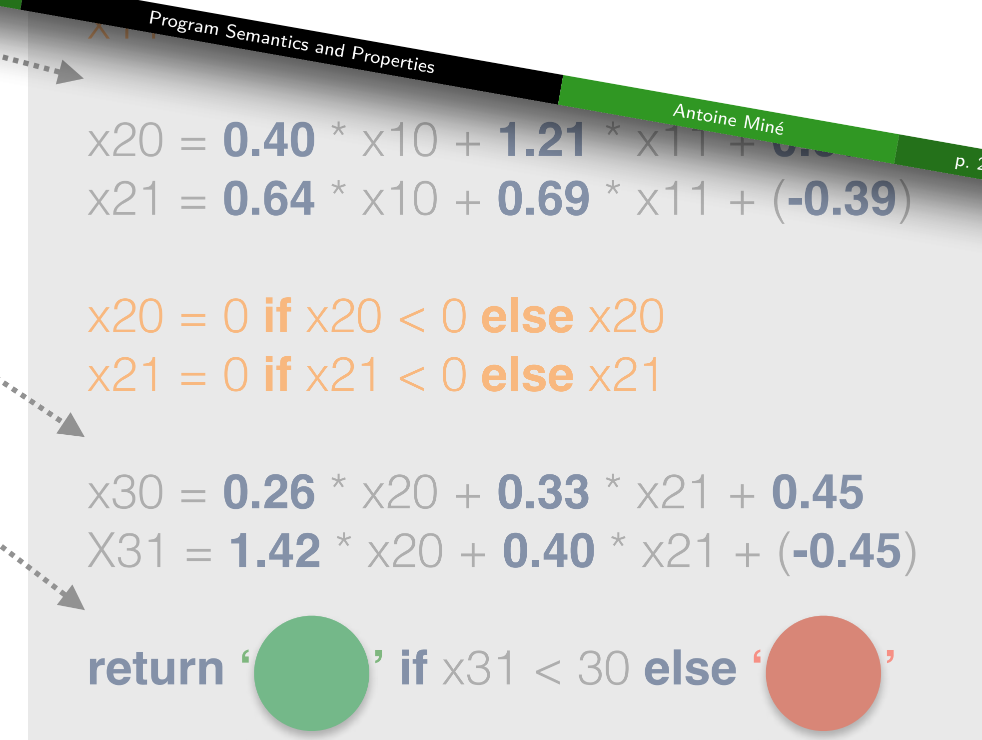
Benefits: uniformity of semantics and properties, $\subseteq$ information order

- given a program *prog* and a property $P \in \mathcal{P}(\mathcal{P}(\Sigma^*))$ the verification problem is an inclusion check:

$$Col(prog) \subseteq P$$

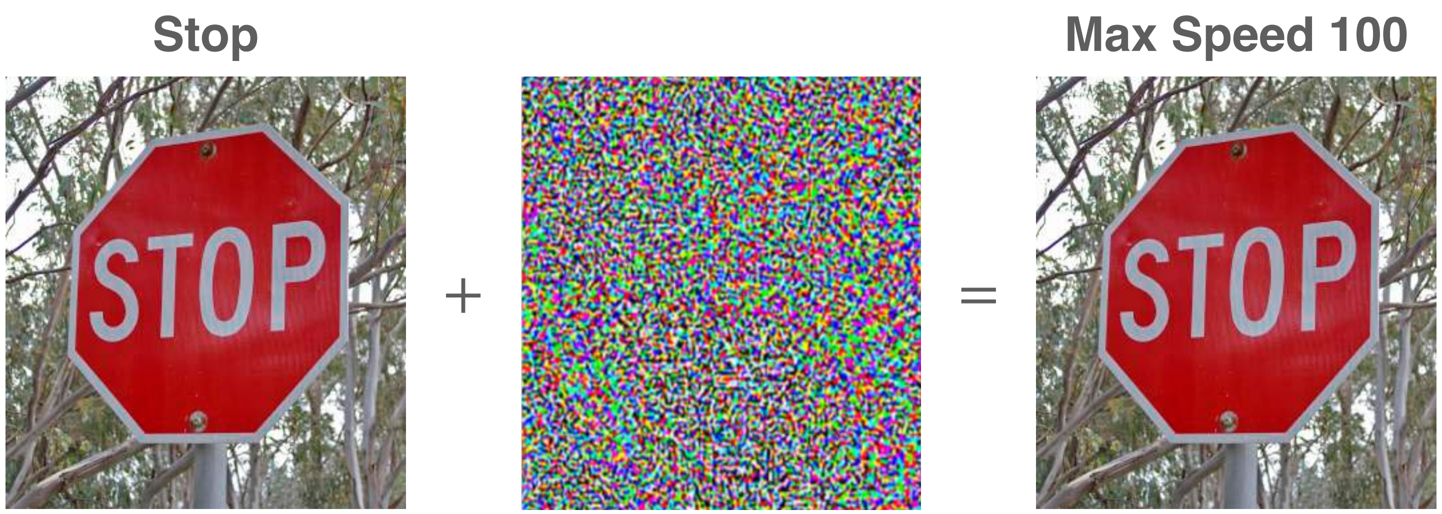
- generally, the collecting semantics cannot be computed, we settle for a weaker property $S^\sharp$ that
  - is sound: $Col(prog) \subseteq S^\sharp$
  - implies the desired property: $S^\sharp \subseteq P$

Course 2 | Program Semantics and Properties | Antoine Miné | p. 24 / 98



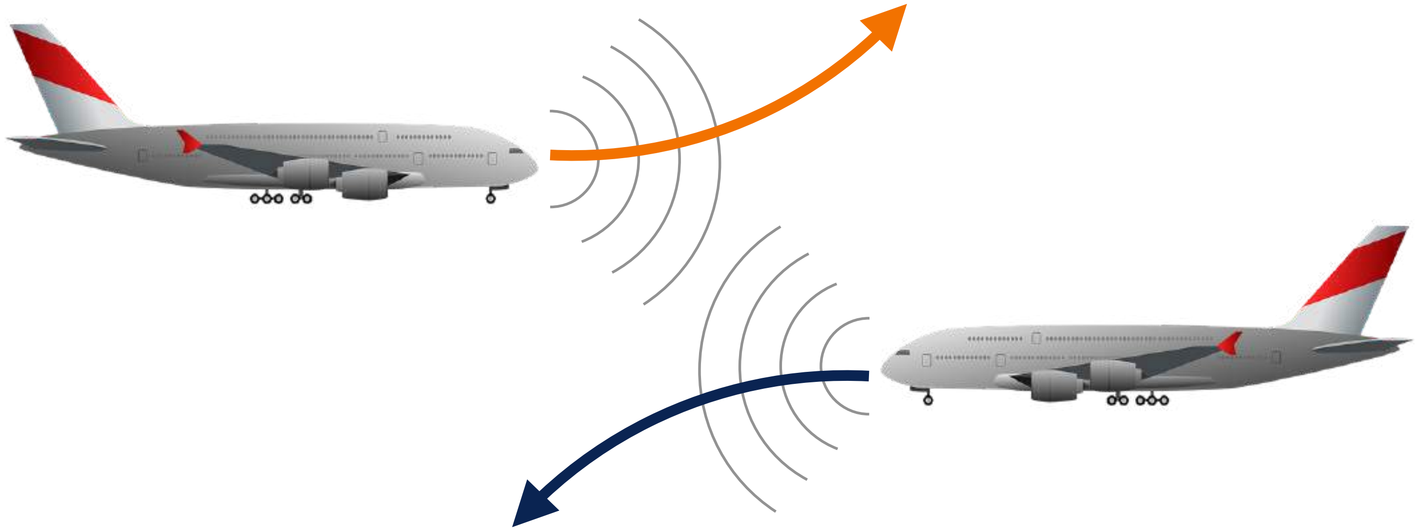
Stability

Goal G3 in [Kurd03]

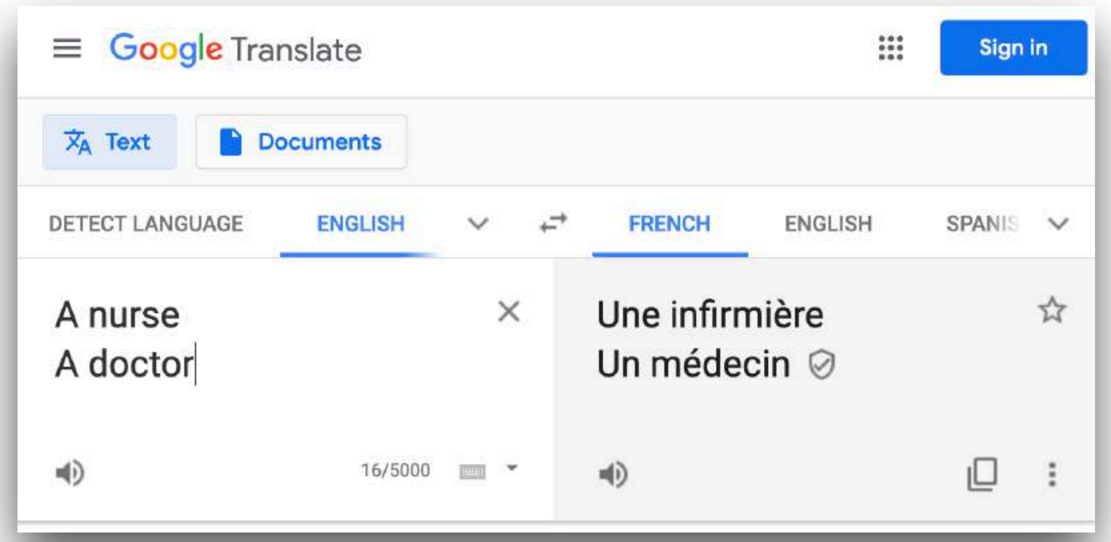


Safety

Goal G4 in [Kurd03]

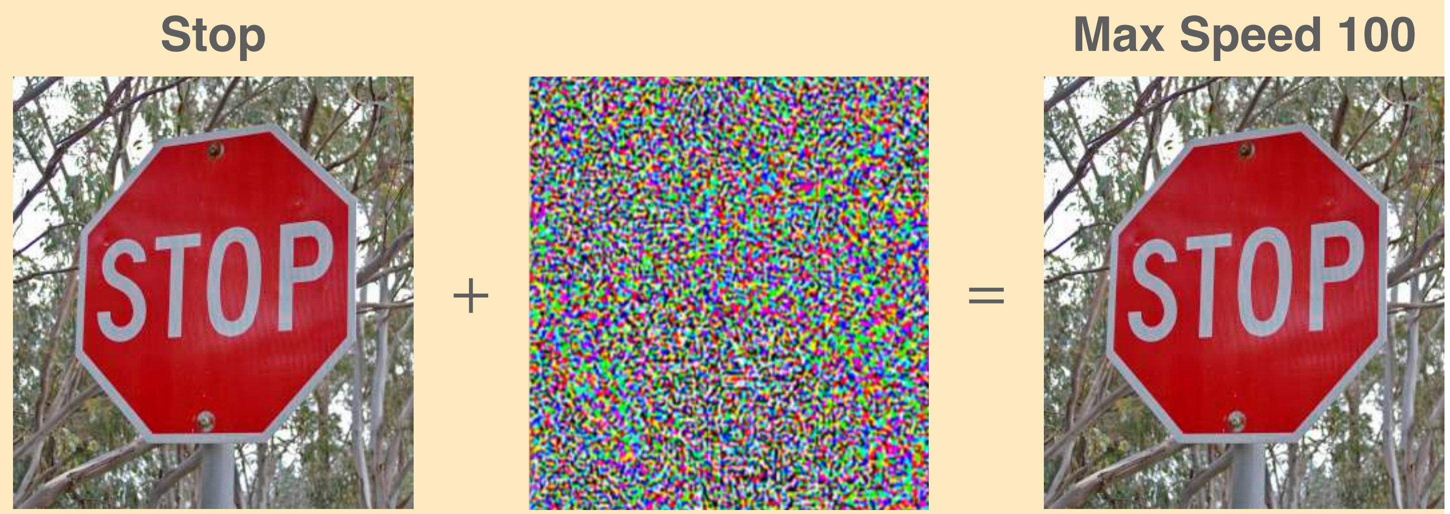


Fairness



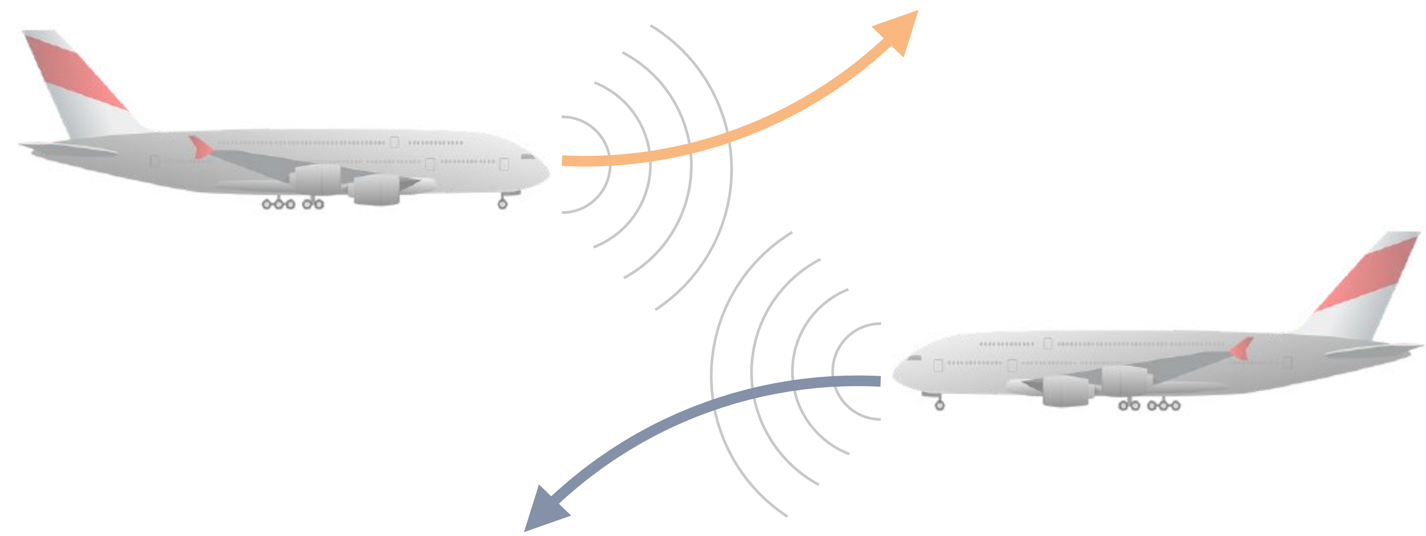
Stability

Goal G3 in [Kurd03]

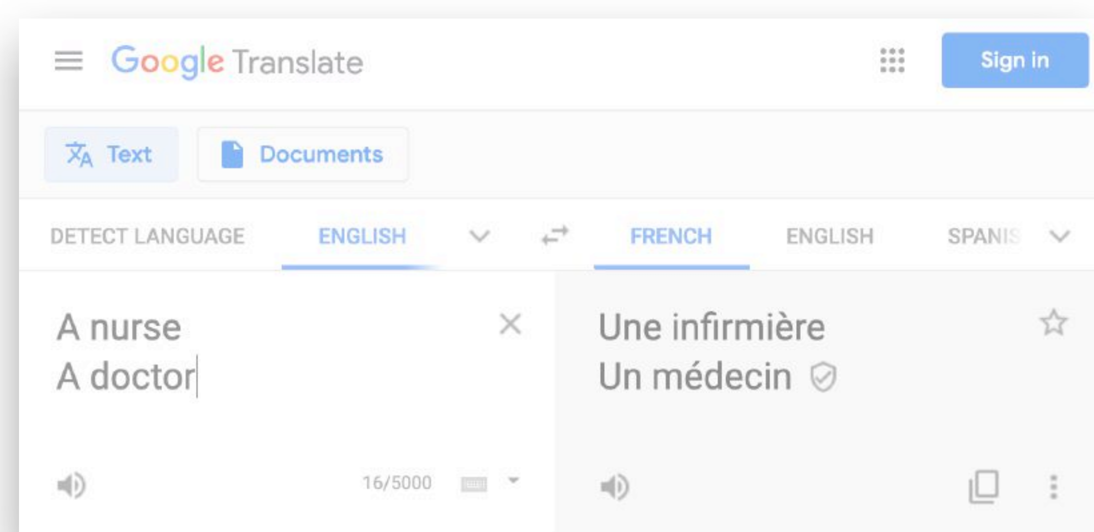


Safety

Goal G4 in [Kurd03]

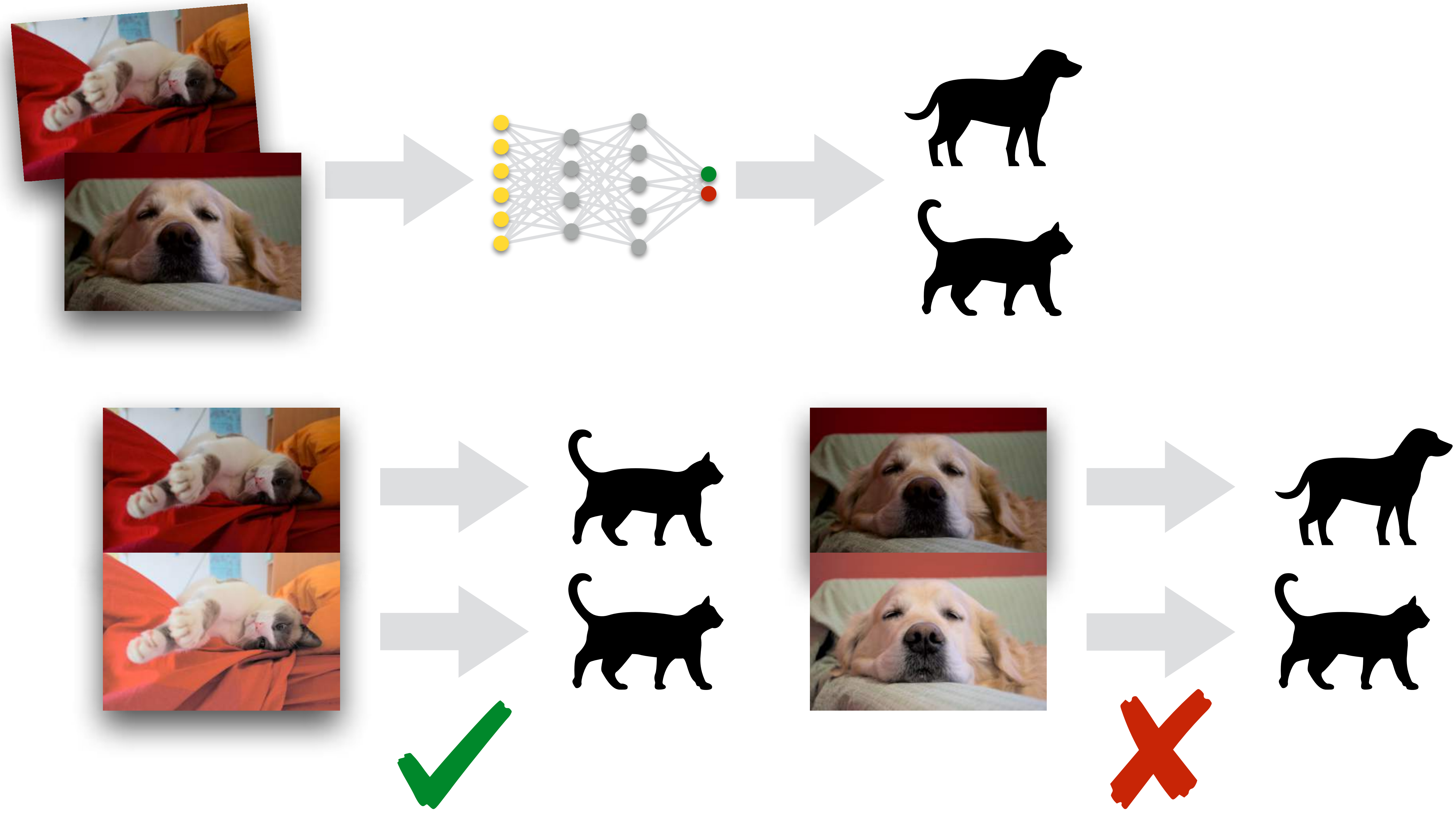


Fairness



Local Stability

The **classification** is **unaffected by small input perturbations**



Local Stability

Distance-Based Perturbations

$$P_{\delta,\epsilon}(\mathbf{x}) \stackrel{\text{def}}{=} \{\mathbf{x}' \in \mathscr{R}^{|L_0|} \mid \delta(\mathbf{x},\mathbf{x}') \leq \epsilon\}$$

Example (L_∞ distance): $P_{\infty,\epsilon}(\mathbf{x}) \stackrel{\text{def}}{=} \{\mathbf{x}' \in \mathscr{R}^{|L_0|} \mid \max_i |\mathbf{x}_i - \mathbf{x}'_i| \leq \epsilon\}$

$$\mathscr{R}_{\mathbf{x}}^{\delta,\epsilon} \stackrel{\text{def}}{=} \{[\![M]\!] \in \mathscr{P}(\Sigma^*) \mid \text{STABLE}_{\mathbf{x}}^{\delta,\epsilon}([\![M]\!])\}$$

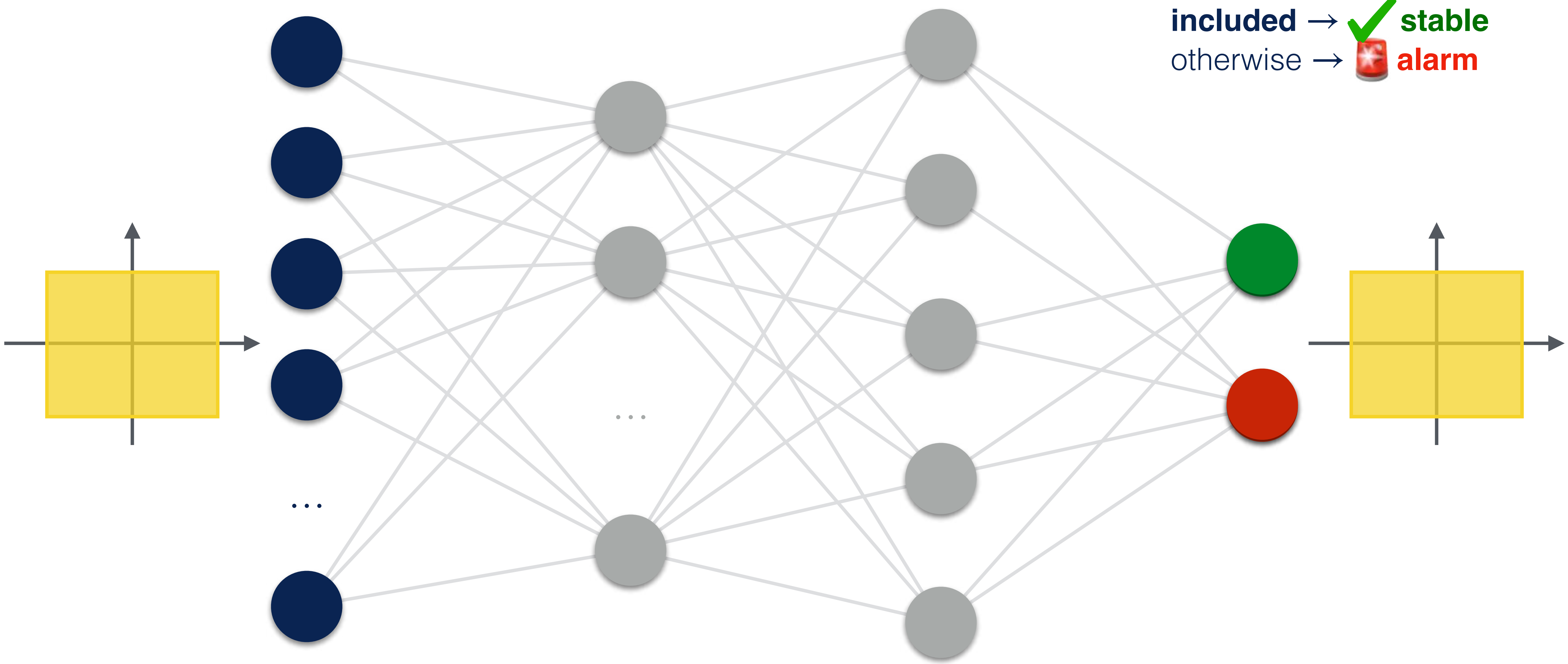
$\mathscr{R}_{\mathbf{x}}^{\delta,\epsilon}$ is the set of all neural networks M (or, rather, their semantics $[\![M]\!]$) that are **stable** in the neighborhood $P_{\delta,\epsilon}(\mathbf{x})$ of a given input $\mathbf{x}$

$$\begin{aligned}\text{STABLE}_{\mathbf{x}}^{\delta,\epsilon}([\![M]\!]) \stackrel{\text{def}}{=} \ & \forall t \in [\![M]\!] : (\exists t' \in [\![M]\!] : \forall 0 \leq i \leq |L_0| : t'_0(x_{0,i}) = \mathbf{x}_i) \\ & \wedge (\exists \mathbf{x}' \in P_{\delta,\epsilon}(\mathbf{x}) : \forall 0 \leq i \leq |L_0| : t_0(x_{0,i}) = \mathbf{x}'_i) \\ & \Rightarrow \max_j t_\omega(x_{N,j}) = \max_j t'_\omega(x_{N,j})\end{aligned}$$

Theorem	Corollary
$M \models \mathscr{R}_{\mathbf{x}}^{\delta,\epsilon} \Leftrightarrow \{[\![M]\!]\} \subseteq \mathscr{R}_{\mathbf{x}}^{\delta,\epsilon}$	$M \models \mathscr{R}_{\mathbf{x}}^{\delta,\epsilon} \Leftrightarrow [\![M]\!] \subseteq \bigcup \mathscr{R}_{\mathbf{x}}^{\delta,\epsilon}$

Static Analysis Methods

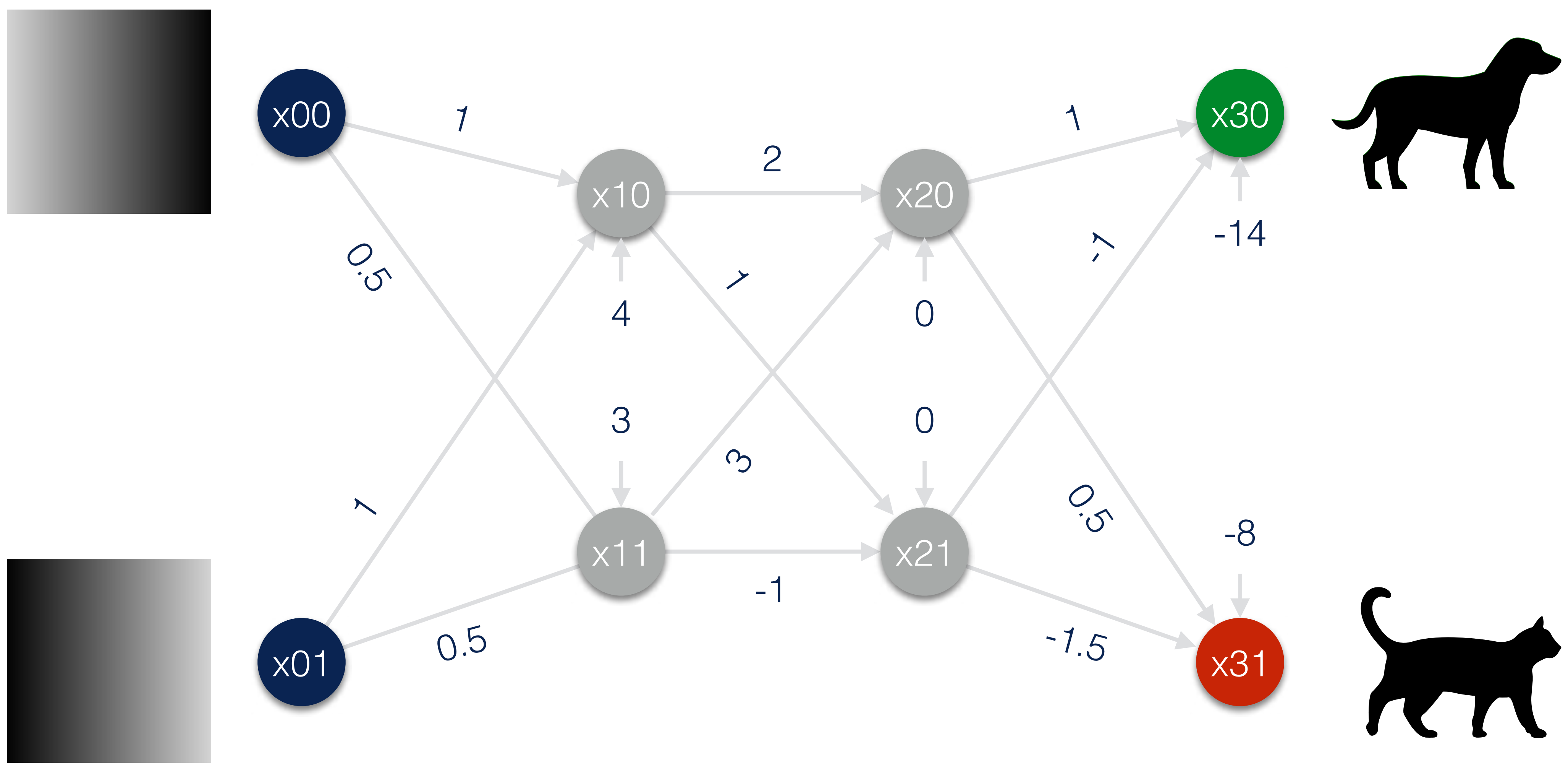
Forward Analysis



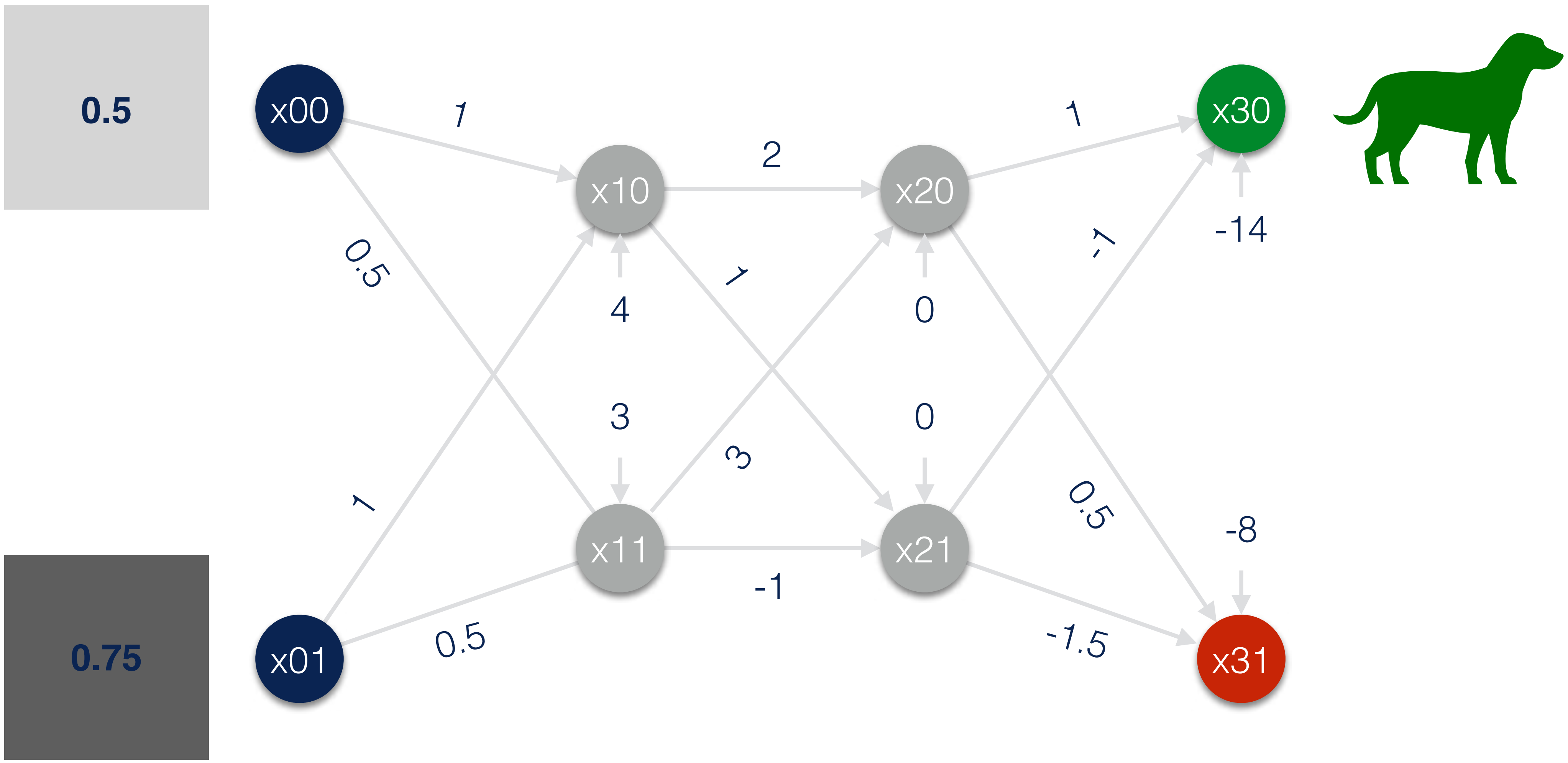
② check output for **inclusion** in **expected output**:
included → ✔ **stable**
otherwise → 🚨 **alarm**

① proceed **forwards from an abstraction** of all possible perturbations

Example



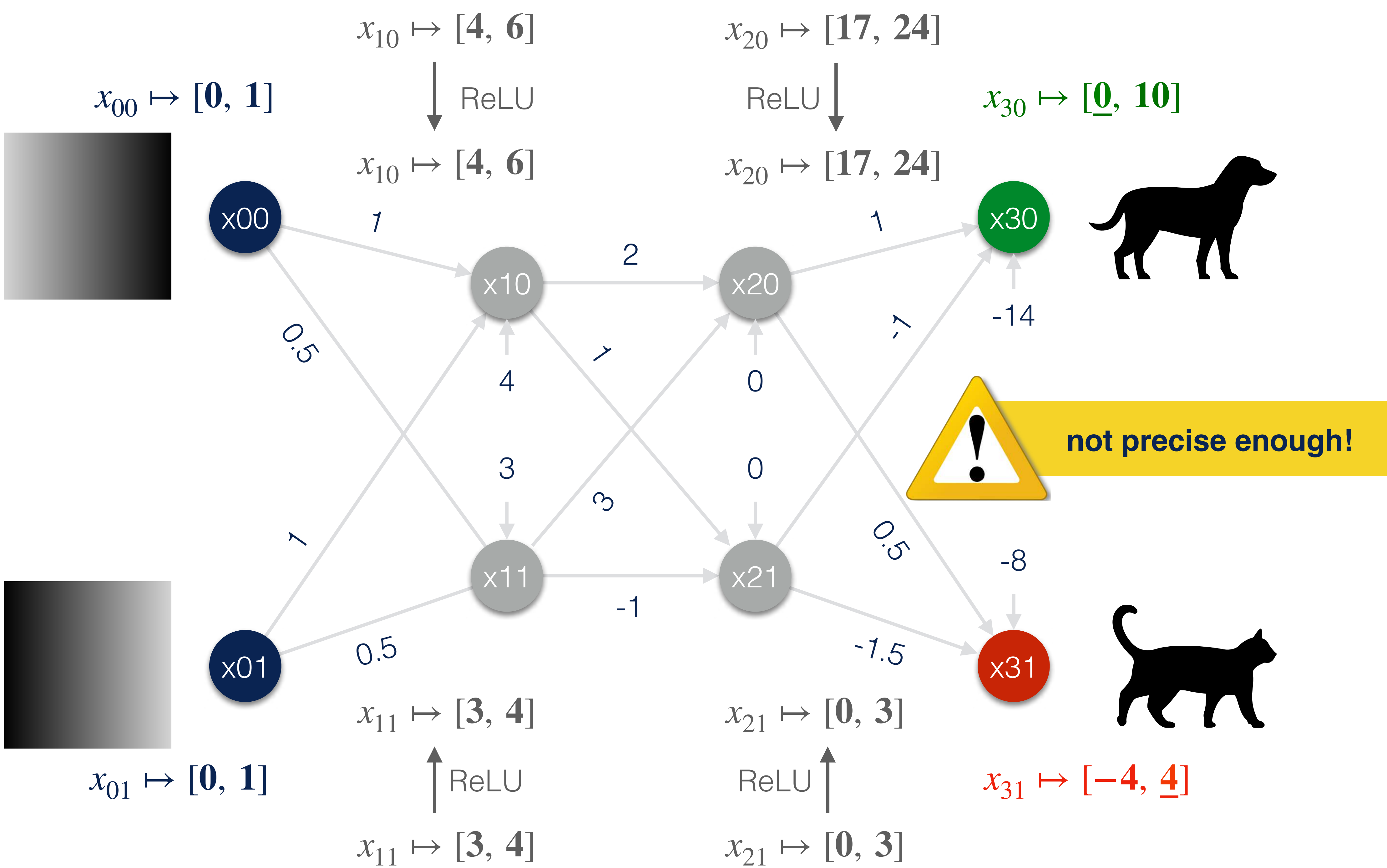
Example



$$P(\langle 0.5, 0.75 \rangle) \stackrel{\text{def}}{=} \{ \mathbf{x} \in \mathscr{R} \times \mathscr{R} \mid 0 \leq \mathbf{x}_0 \leq 1 \wedge 0 \leq \mathbf{x}_1 \leq 1 \}$$

Interval Domain

$$x_{i,j} \mapsto [a, b]$$
$$a, b \in \mathscr{R}$$



Interval Domain

with Symbolic Constant Propagation [Li19]

each neuron as a linear combination of the inputs and the previous ReLUs

$$x_{i,j} \mapsto \begin{cases} \sum_{k=0}^{i-1} \mathbf{c}_k \cdot \mathbf{x}_k + \mathbf{c} & \mathbf{c}_k, \mathbf{c} \in \mathscr{R}^{|\mathbf{X}_k|} \\ [a, b] & a, b \in \mathscr{R} \end{cases}$$

$x_{i-1,0} \mapsto \mathbf{E_{i-1,0}}$

$\ldots$

$x_{i-1,j} \mapsto \mathbf{E_{i-1,j}}$

$\ldots$

$$\xrightarrow{x_{i,j} = \sum_k w_{j,k}^{i-1} \cdot x_{i-1,k} + b_{i,j}}$$

$$x_{i,j} \mapsto \sum_k w_{j,k}^{i-1} \cdot \mathbf{E_{i-1,k}} + b_{i,j}$$

$$x_{i,j} \mapsto \begin{cases} \mathbf{E_{i,j}} \\ \mathbf{[a, b]} \end{cases} \xrightarrow{\text{ReLU}}$$

$$x_{i,j} \mapsto \begin{cases} \mathbf{E_{i,j}} \\ \mathbf{[a, b]} \end{cases} \qquad 0 \leq a$$

$$x_{i,j} \mapsto \begin{cases} \mathbf{x_{i,j}} \\ \mathbf{[0, b]} \end{cases} \qquad a < 0 \wedge 0 < b$$

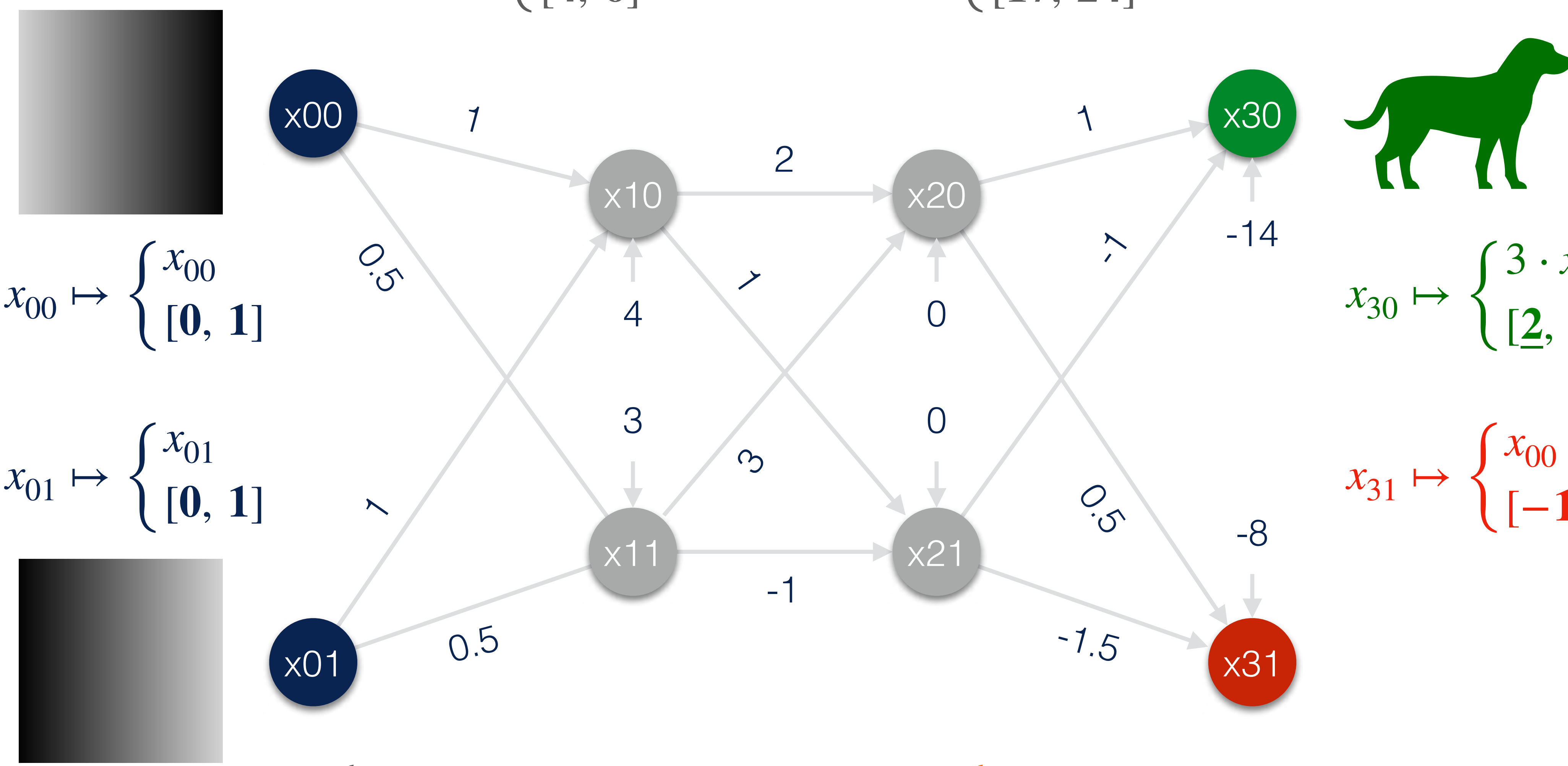
$$x_{i,j} \mapsto \begin{cases} \mathbf{0} \\ \mathbf{[0, 0]} \end{cases} \qquad b \leq 0$$

J. Li et al. - Analyzing Deep Neural Networks with Symbolic Propagation (SAS 2019)

Interval Domain

with Symbolic Constant Propagation [Li19]

$$x_{10} \mapsto \begin{cases} x_{00} + x_{01} + 4 \\ [\mathbf{4},\ \mathbf{6}] \end{cases} \qquad x_{20} \mapsto \begin{cases} 2 \cdot (x_{00} + x_{01} + 4) + 3 \cdot (0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3) \\ [\mathbf{17},\ \mathbf{24}] \end{cases}$$



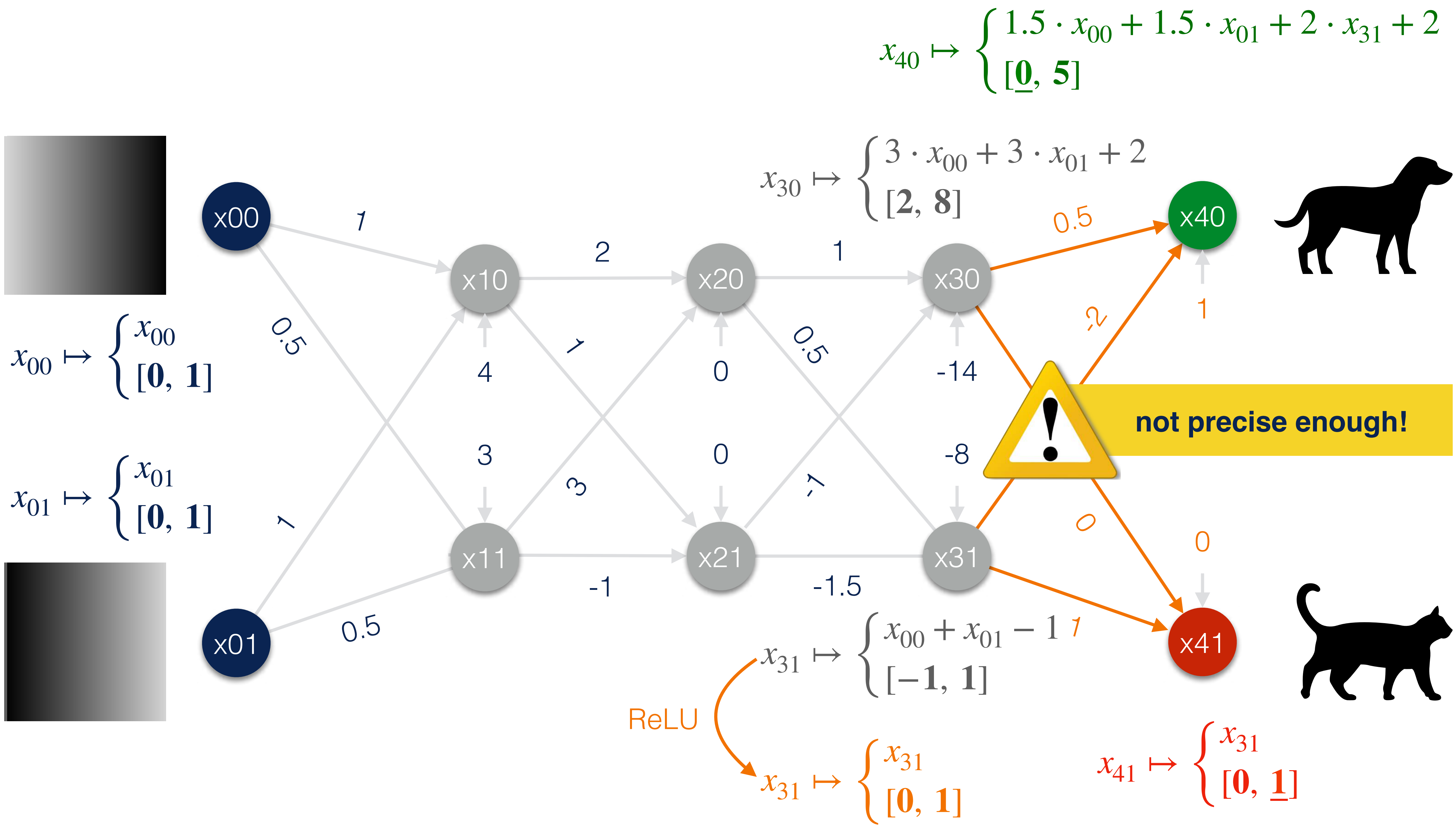
$$x_{00} \mapsto \begin{cases} x_{00} \\ [\mathbf{0},\ \mathbf{1}] \end{cases} \qquad x_{01} \mapsto \begin{cases} x_{01} \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{30} \mapsto \begin{cases} 3 \cdot x_{00} + 3 \cdot x_{01} + 2 \\ [\underline{\mathbf{2}},\ \mathbf{8}] \end{cases} \qquad x_{31} \mapsto \begin{cases} x_{00} + x_{01} - 1 \\ [\mathbf{-1},\ \underline{\mathbf{1}}] \end{cases}$$

$$x_{11} \mapsto \begin{cases} 0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3 \\ [\mathbf{3},\ \mathbf{4}] \end{cases} \qquad x_{21} \mapsto \begin{cases} (x_{00} + x_{01} + 4) - 1 \cdot (0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3) \\ [\mathbf{1},\ \mathbf{2}] \end{cases}$$

Interval Domain

with Symbolic Constant Propagation [Li19]



DeepPoly [Singh19]

maintain symbolic lower- and upper-bounds for each neuron + convex ReLU approximations

$$x_{i+1,j} \mapsto \begin{cases} [\sum_k c_{i,k} \cdot x_{i,k} + c,\ \sum_k d_{i,k} \cdot x_{i,k} + d] & c_{i,k}, c, d_{i,k}, d \in \mathscr{R} \\ [a,\ b] & a, b \in \mathscr{R} \end{cases}$$

$$x_{i,j} \mapsto \begin{cases} [\mathbf{L_{i,j}}, \mathbf{U_{i,j}}] \\ [\mathbf{a}, \mathbf{b}] \end{cases}$$

ReLU $0 \leq a$:

$$x_{i,j} \mapsto \begin{cases} [\mathbf{L_{i,j}}, \mathbf{U_{i,j}}] \\ [\mathbf{a}, \mathbf{b}] \end{cases}$$

ReLU $a < 0 \wedge 0 < b$

$b \leq -a$:

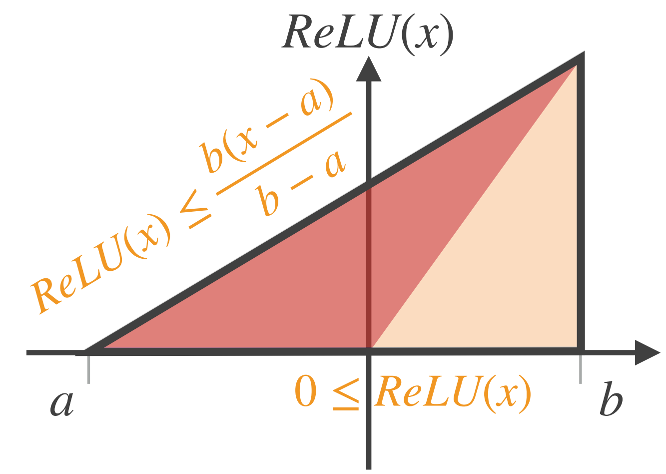
$$x_{i,j} \mapsto \begin{cases} \left[\mathbf{0}, \dfrac{\mathbf{b(x_{i,j} - a)}}{\mathbf{b - a}}\right] \\ [\mathbf{0}, \mathbf{b}] \end{cases}$$

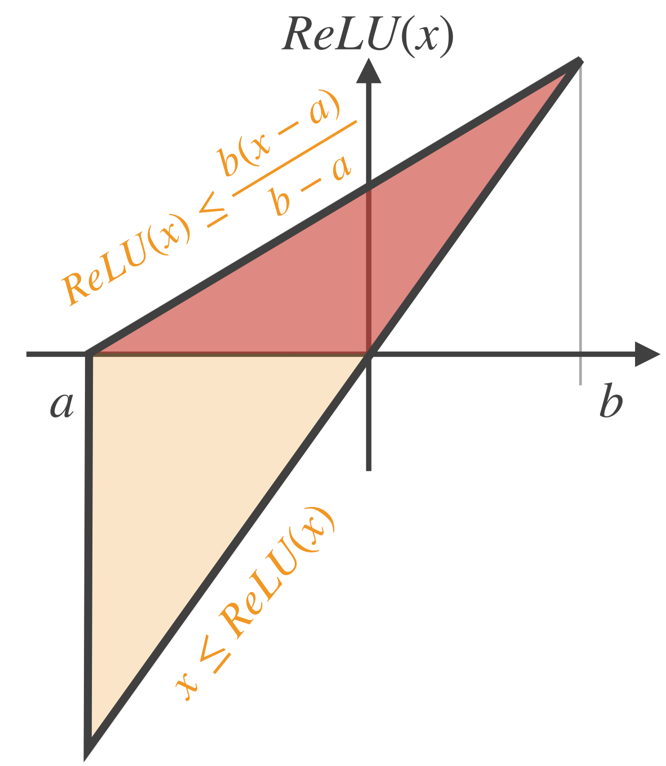
$-a < b$:

$$x_{i,j} \mapsto \begin{cases} \left[\mathbf{x_{i,j}}, \dfrac{\mathbf{b(x_{i,j} - a)}}{\mathbf{b - a}}\right] \\ [\mathbf{a}, \mathbf{b}] \end{cases}$$

ReLU $b \leq 0$:

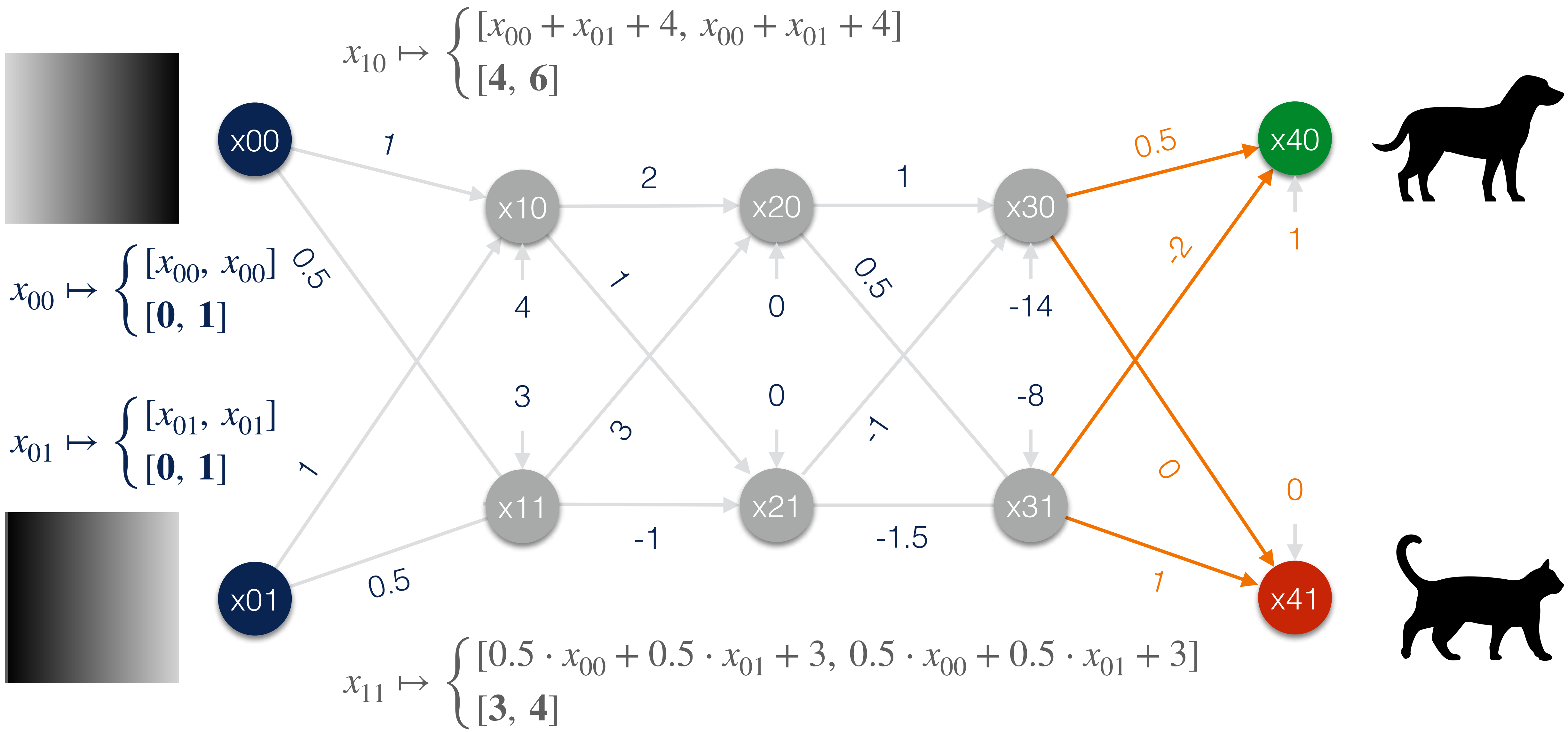
$$x_{i,j} \mapsto \begin{cases} [\mathbf{0}, \mathbf{0}] \\ [\mathbf{0}, \mathbf{0}] \end{cases}$$



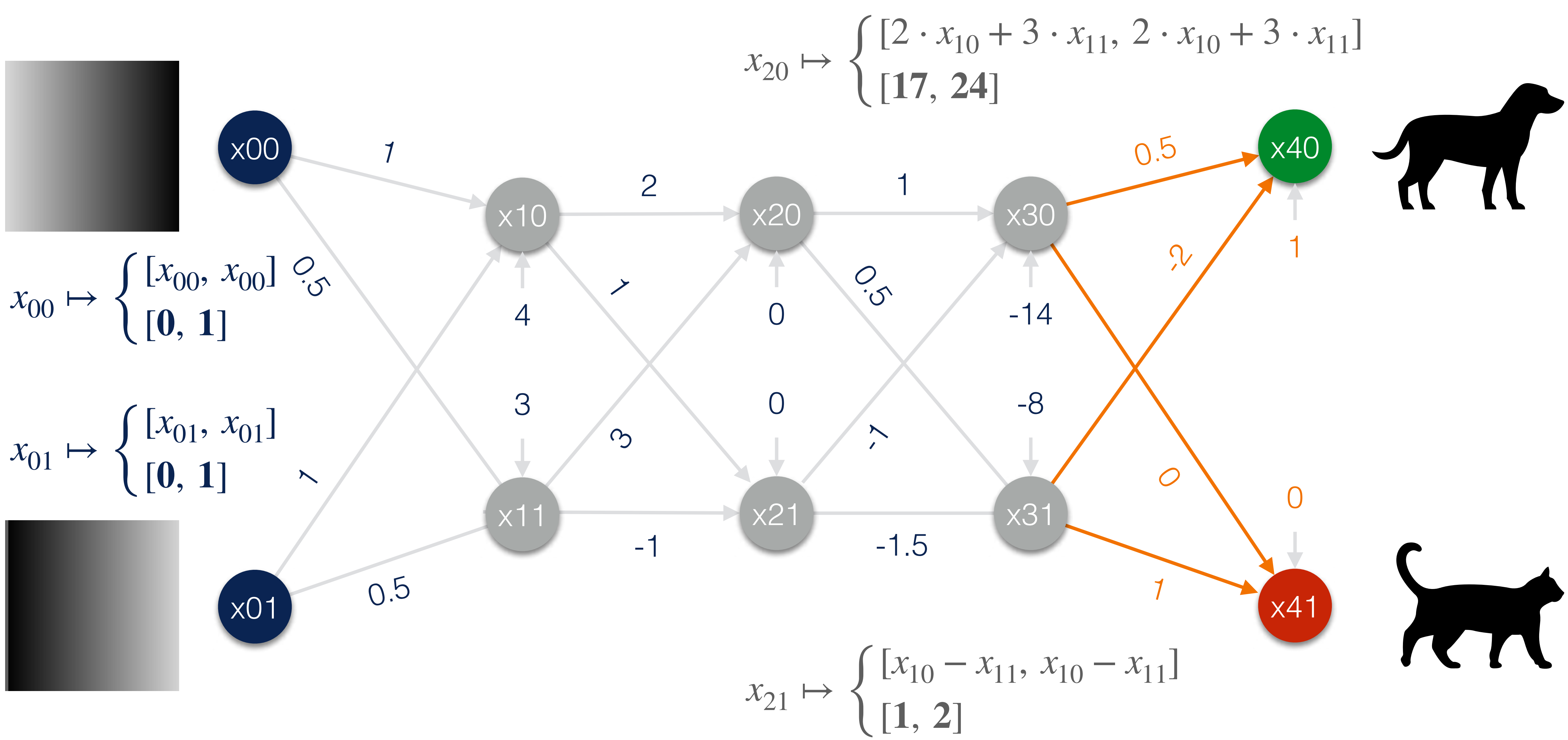


G. Singh, T. Gehr, M. Püschel, and M. Vechev - An Abstract Domain for Certifying Neural Networks (POPL 2019)

DeepPoly [Singh19]



DeepPoly [Singh19]



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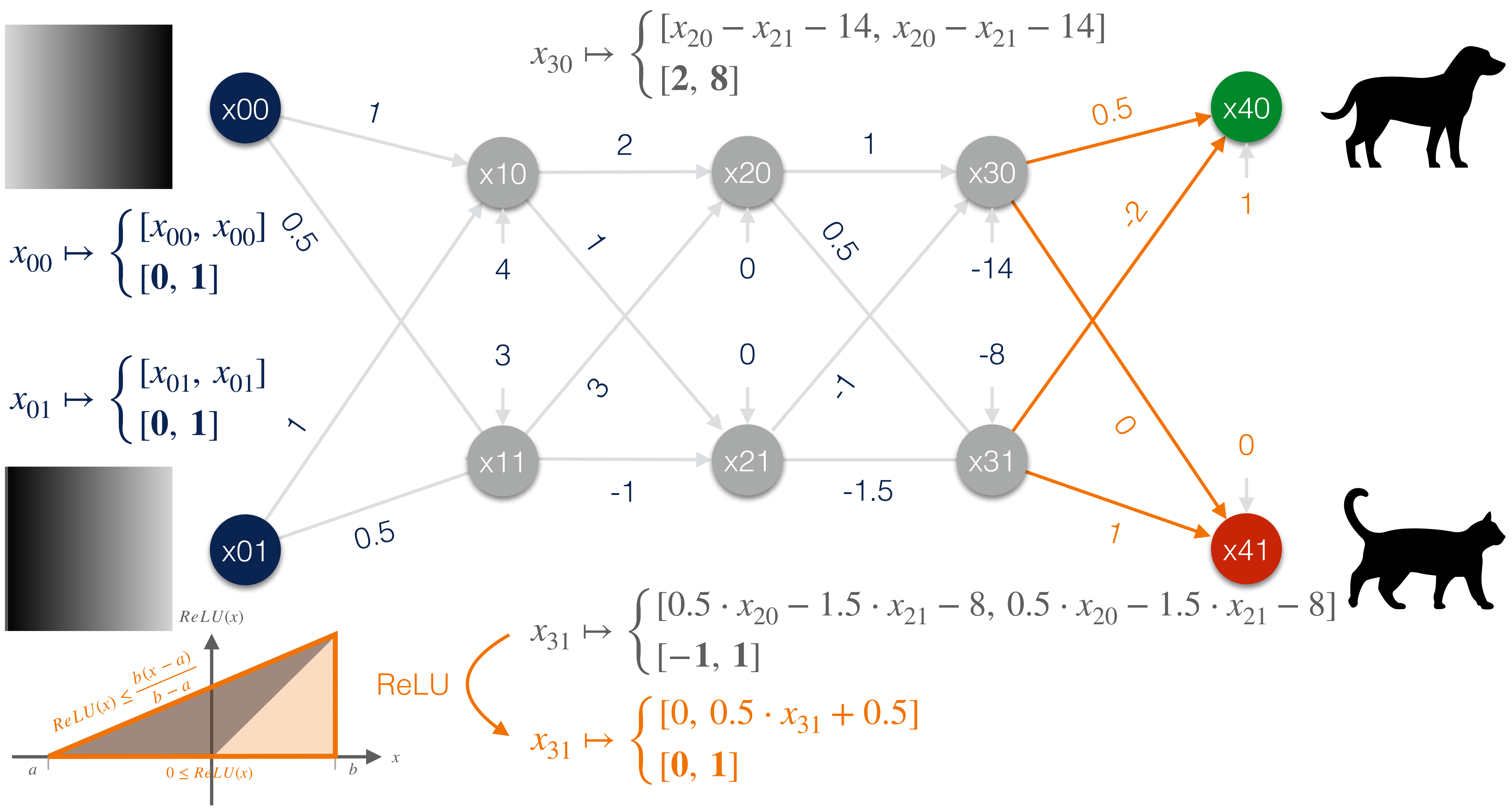
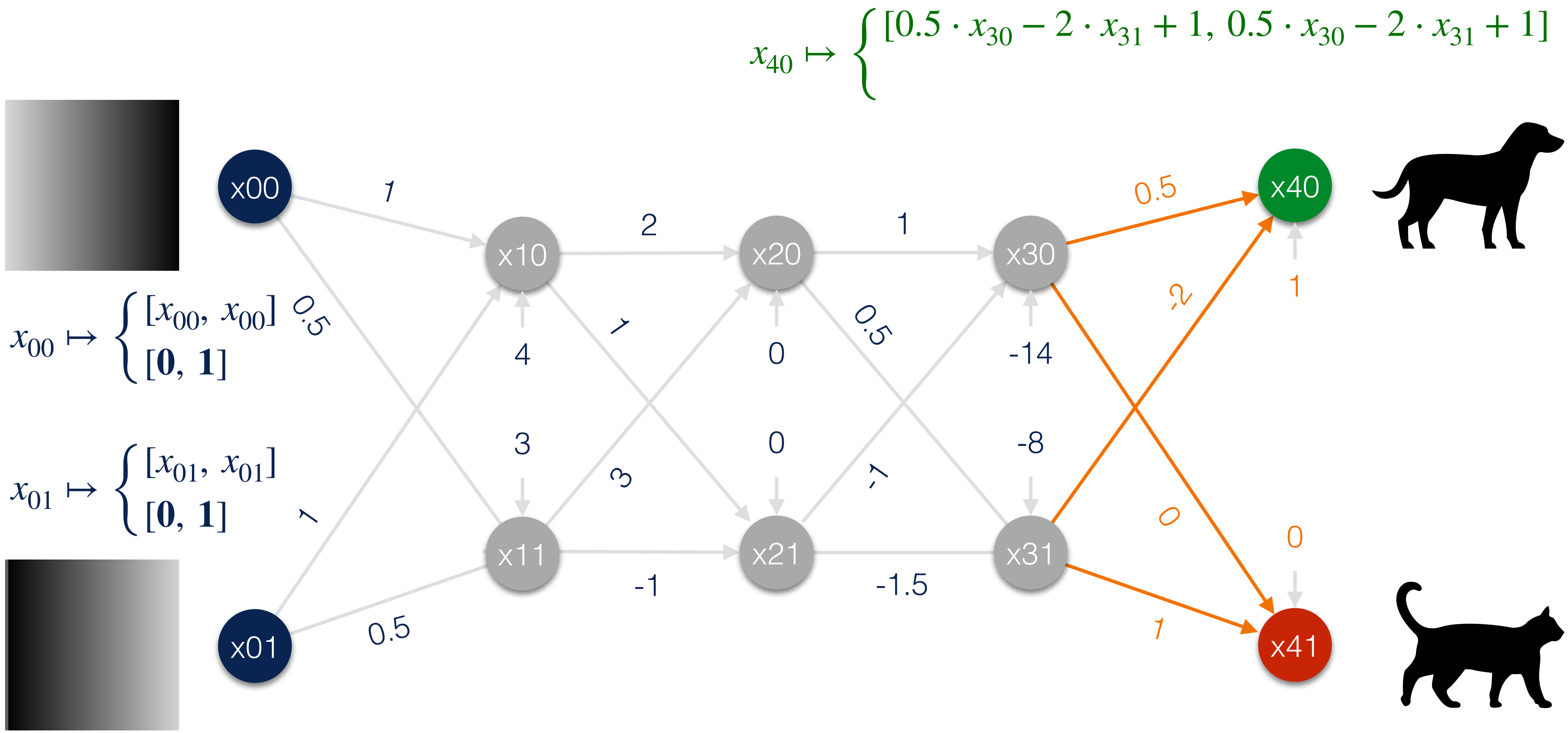


DeepPoly [Singh19]



DeepPoly [Singh19]

$$x_{00} \mapsto \begin{cases} [x_{00},\ x_{00}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases} \qquad x_{01} \mapsto \begin{cases} [x_{01},\ x_{01}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{10} \mapsto \begin{cases} [x_{00} + x_{01} + 4,\ x_{00} + x_{01} + 4] \\ [\mathbf{4},\ \mathbf{6}] \end{cases} \qquad x_{11} \mapsto \begin{cases} [0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3,\ 0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3] \\ [\mathbf{3},\ \mathbf{4}] \end{cases}$$

$$x_{20} \mapsto \begin{cases} [2 \cdot x_{10} + 3 \cdot x_{11},\ 2 \cdot x_{10} + 3 \cdot x_{11}] \\ [\mathbf{17},\ \mathbf{24}] \end{cases} \qquad x_{21} \mapsto \begin{cases} [x_{10} - x_{11},\ x_{10} - x_{11}] \\ [\mathbf{1},\ \mathbf{2}] \end{cases}$$

$$x_{30} \mapsto \begin{cases} [x_{20} - x_{21} - 14,\ x_{20} - x_{21} - 14] \\ [\mathbf{2},\ \mathbf{8}] \end{cases} \qquad x_{31} \mapsto \begin{cases} [0,\ 0.5 \cdot (0.5 \cdot x_{20} - 1.5 \cdot x_{21} - 8) + 0.5] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{40} \mapsto \begin{cases} [0.5 \cdot x_{30} - 2 \cdot x_{31} + 1,\ 0.5 \cdot x_{30} - 2 \cdot x_{31} + 1] \\ \end{cases}$$

$$\mapsto \begin{cases} [x_{21} + 1,\ 0.5 \cdot x_{20} - 0.5 \cdot x_{21} - 6] \\ \end{cases}$$

DeepPoly [Singh19]

$$x_{00} \mapsto \begin{cases} [x_{00},\ x_{00}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases} \qquad x_{01} \mapsto \begin{cases} [x_{01},\ x_{01}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{10} \mapsto \begin{cases} [x_{00} + x_{01} + 4,\ x_{00} + x_{01} + 4] \\ [\mathbf{4},\ \mathbf{6}] \end{cases} \qquad x_{11} \mapsto \begin{cases} [0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3,\ 0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3] \\ [\mathbf{3},\ \mathbf{4}] \end{cases}$$

$$x_{20} \mapsto \begin{cases} [2 \cdot x_{10} + 3 \cdot x_{11},\ 2 \cdot x_{10} + 3 \cdot x_{11}] \\ [\mathbf{17},\ \mathbf{24}] \end{cases} \qquad x_{21} \mapsto \begin{cases} [x_{10} - x_{11},\ x_{10} - x_{11}] \\ [\mathbf{1},\ \mathbf{2}] \end{cases}$$

$$x_{30} \mapsto \begin{cases} [x_{20} - x_{21} - 14,\ x_{20} - x_{21} - 14] \\ [\mathbf{2},\ \mathbf{8}] \end{cases} \qquad x_{31} \mapsto \begin{cases} [0,\ 0.5 \cdot (0.5 \cdot x_{20} - 1.5 \cdot x_{21} - 8) + 0.5] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{40} \mapsto \begin{cases} [0.5 \cdot x_{30} - 2 \cdot x_{31} + 1,\ 0.5 \cdot x_{30} - 2 \cdot x_{31} + 1] \\ \end{cases}$$

$$\mapsto \begin{cases} [x_{21} + 1,\ 0.5 \cdot x_{20} - 0.5 \cdot x_{21} - 6] \\ \end{cases}$$

$$\mapsto \begin{cases} [x_{10} - x_{11} + 1,\ 0.5 \cdot x_{10} + 2 \cdot x_{11} - 6] \\ \end{cases}$$

DeepPoly [Singh19]

$$x_{00} \mapsto \begin{cases} [x_{00},\ x_{00}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases} \qquad x_{01} \mapsto \begin{cases} [x_{01},\ x_{01}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{10} \mapsto \begin{cases} [x_{00} + x_{01} + 4,\ x_{00} + x_{01} + 4] \\ [\mathbf{4},\ \mathbf{6}] \end{cases} \qquad x_{11} \mapsto \begin{cases} [0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3,\ 0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3] \\ [\mathbf{3},\ \mathbf{4}] \end{cases}$$

$$x_{20} \mapsto \begin{cases} [2 \cdot x_{10} + 3 \cdot x_{11},\ 2 \cdot x_{10} + 3 \cdot x_{11}] \\ [\mathbf{17},\ \mathbf{24}] \end{cases} \qquad x_{21} \mapsto \begin{cases} [x_{10} - x_{11},\ x_{10} - x_{11}] \\ [\mathbf{1},\ \mathbf{2}] \end{cases}$$

$$x_{30} \mapsto \begin{cases} [x_{20} + x_{21} - 14,\ x_{20} - x_{21} - 14] \\ [\mathbf{2},\ \mathbf{8}] \end{cases} \qquad x_{31} \mapsto \begin{cases} [0,\ 0.5 \cdot (0.5 \cdot x_{20} - 1.5 \cdot x_{21} - 8) + 0.5] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{40} \mapsto \begin{cases} [0.5 \cdot x_{30} - 2 \cdot x_{31} + 1,\ 0.5 \cdot x_{30} - 2 \cdot x_{31} + 1] \\ \end{cases}$$

$$\mapsto \begin{cases} [x_{21} + 1,\ 0.5 \cdot x_{20} - 0.5 \cdot x_{21} - 6] \\ \end{cases}$$

$$\mapsto \begin{cases} [x_{10} - x_{11} + 1,\ 0.5 \cdot x_{10} + 2 \cdot x_{11} - 6] \\ \end{cases}$$

$$\mapsto \begin{cases} [0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 2,\ 1.5 \cdot x_{00} + 1.5 \cdot x_{11} + 2] \\ \end{cases}$$

DeepPoly [Singh19]

$$x_{00} \mapsto \begin{cases} [x_{00},\ x_{00}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{01} \mapsto \begin{cases} [x_{01},\ x_{01}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{10} \mapsto \begin{cases} [x_{00} + x_{01} + 4,\ x_{00} + x_{01} + 4] \\ [\mathbf{4},\ \mathbf{6}] \end{cases}$$

$$x_{11} \mapsto \begin{cases} [0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3,\ 0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3] \\ [\mathbf{3},\ \mathbf{4}] \end{cases}$$

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$$x_{30} \mapsto \begin{cases} [x_{20} - x_{21} - 14,\ x_{20} - x_{21} - 14] \\ [\mathbf{2},\ \mathbf{8}] \end{cases}$$

$$x_{31} \mapsto \begin{cases} [0,\ 0.5 \cdot (0.5 \cdot x_{20} - 1.5 \cdot x_{21} - 8) + 0.5] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

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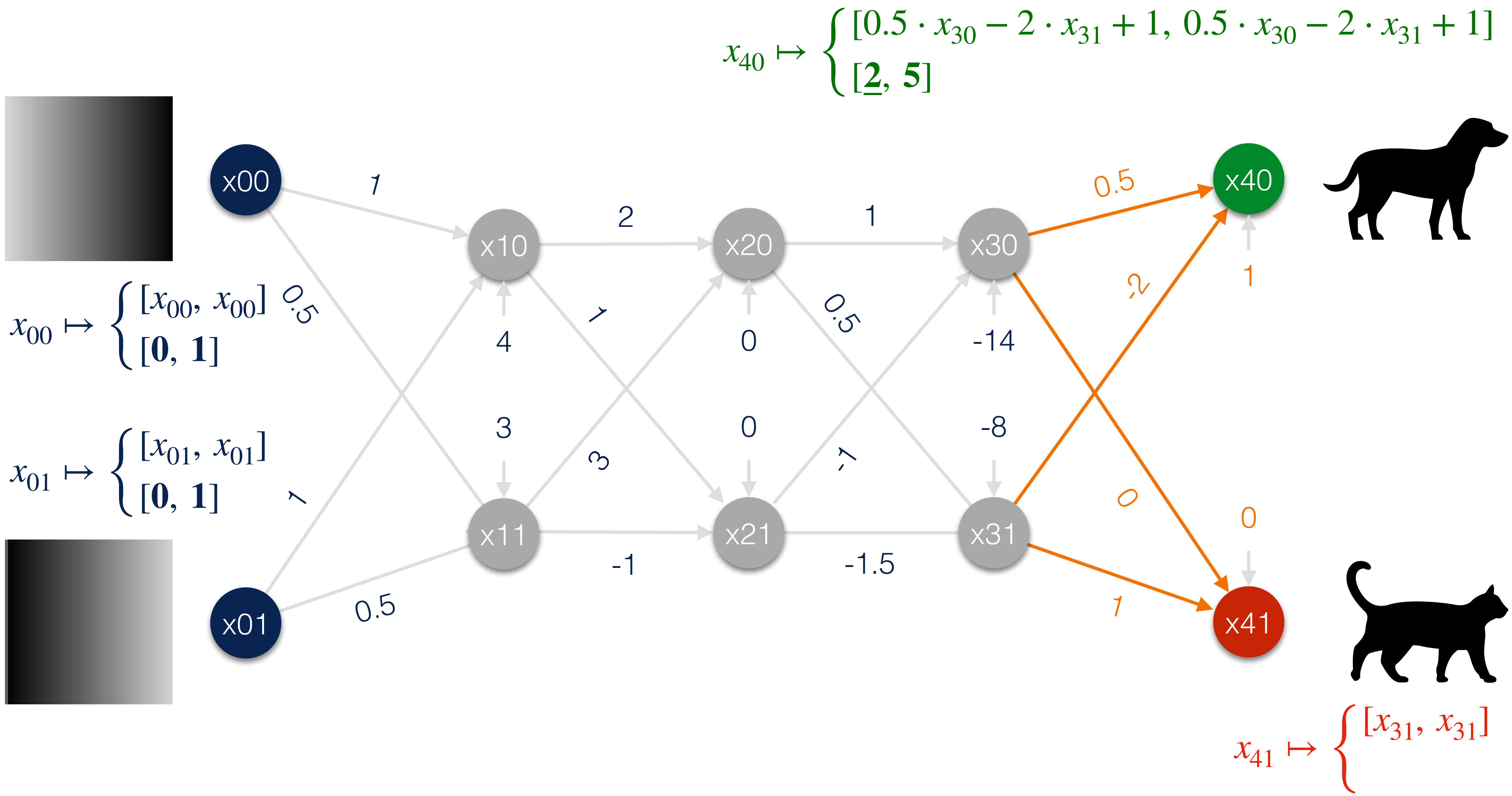
$$\mapsto \begin{cases} [x_{21} + 1,\ 0.5 \cdot x_{20} - 0.5 \cdot x_{21} - 6] \\ \end{cases}$$

$$\mapsto \begin{cases} [x_{10} - x_{11} + 1,\ 0.5 \cdot x_{10} + 2 \cdot x_{11} - 6] \\ \end{cases}$$

$$\mapsto \begin{cases} [0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 2,\ 1.5 \cdot x_{00} + 1.5 \cdot x_{11} + 2] \\ [\underline{\mathbf{2}},\ \mathbf{5}] \end{cases}$$

DeepPoly [Singh19]



DeepPoly [Singh19]

$$x_{00} \mapsto \begin{cases} [x_{00},\ x_{00}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases} \qquad x_{01} \mapsto \begin{cases} [x_{01},\ x_{01}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{10} \mapsto \begin{cases} [x_{00} + x_{01} + 4,\ x_{00} + x_{01} + 4] \\ [\mathbf{4},\ \mathbf{6}] \end{cases} \qquad x_{11} \mapsto \begin{cases} [0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3,\ 0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3] \\ [\mathbf{3},\ \mathbf{4}] \end{cases}$$

$$x_{20} \mapsto \begin{cases} [2 \cdot x_{10} + 3 \cdot x_{11},\ 2 \cdot x_{10} + 3 \cdot x_{11}] \\ [\mathbf{17},\ \mathbf{24}] \end{cases} \qquad x_{21} \mapsto \begin{cases} [x_{10} - x_{11},\ x_{10} - x_{11}] \\ [\mathbf{1},\ \mathbf{2}] \end{cases}$$

$$x_{30} \mapsto \begin{cases} [x_{20} - x_{21} - 14,\ x_{20} - x_{21} - 14] \\ [\mathbf{2},\ \mathbf{8}] \end{cases} \qquad x_{31} \mapsto \begin{cases} [0,\ 0.5 \cdot (0.5 \cdot x_{20} - 1.5 \cdot x_{21} - 8) + 0.5] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{41} \mapsto \begin{cases} [x_{31},\ x_{31}] \\ \end{cases}$$

$$\mapsto \begin{cases} [0,\ 0.25 \cdot x_{20} - 0.75 \cdot x_{21} - 3.5] \\ \end{cases}$$

DeepPoly [Singh19]

$x_{00} \mapsto \begin{cases} [x_{00},\ x_{00}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$

$x_{01} \mapsto \begin{cases} [x_{01},\ x_{01}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$

$x_{10} \mapsto \begin{cases} [x_{00} + x_{01} + 4,\ x_{00} + x_{01} + 4] \\ [\mathbf{4},\ \mathbf{6}] \end{cases}$

$x_{11} \mapsto \begin{cases} [0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3,\ 0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3] \\ [\mathbf{3},\ \mathbf{4}] \end{cases}$

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$x_{21} \mapsto \begin{cases} [x_{10} - x_{11},\ x_{10} - x_{11}] \\ [\mathbf{1},\ \mathbf{2}] \end{cases}$

$x_{30} \mapsto \begin{cases} [x_{20} - x_{21} - 14,\ x_{20} - x_{21} - 14] \\ [\mathbf{2},\ \mathbf{8}] \end{cases}$

$x_{31} \mapsto \begin{cases} [0,\ 0.5 \cdot (0.5 \cdot x_{20} - 1.5 \cdot x_{21} - 8) + 0.5] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$

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DeepPoly [Singh19]

$$x_{00} \mapsto \begin{cases} [x_{00},\ x_{00}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases} \qquad x_{01} \mapsto \begin{cases} [x_{01},\ x_{01}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{10} \mapsto \begin{cases} [x_{00} + x_{01} + 4,\ x_{00} + x_{01} + 4] \\ [\mathbf{4},\ \mathbf{6}] \end{cases} \qquad x_{11} \mapsto \begin{cases} [0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3,\ 0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3] \\ [\mathbf{3},\ \mathbf{4}] \end{cases}$$

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$$x_{30} \mapsto \begin{cases} [x_{20} - x_{21} - 14,\ x_{20} - x_{21} - 14] \\ [\mathbf{2},\ \mathbf{8}] \end{cases} \qquad x_{31} \mapsto \begin{cases} [0,\ 0.5 \cdot (0.5 \cdot x_{20} - 1.5 \cdot x_{21} - 8) + 0.5] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

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$$\mapsto \begin{cases} [0,\ 0.5 \cdot x_{00} + 0.5 \cdot x_{01}] \end{cases}$$

DeepPoly [Singh19]

$$x_{00} \mapsto \begin{cases} [x_{00},\ x_{00}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases} \qquad x_{01} \mapsto \begin{cases} [x_{01},\ x_{01}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{10} \mapsto \begin{cases} [x_{00} + x_{01} + 4,\ x_{00} + x_{01} + 4] \\ [\mathbf{4},\ \mathbf{6}] \end{cases} \qquad x_{11} \mapsto \begin{cases} [0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3,\ 0.5 \cdot x_{00} + 0.5 \cdot x_{01} + 3] \\ [\mathbf{3},\ \mathbf{4}] \end{cases}$$

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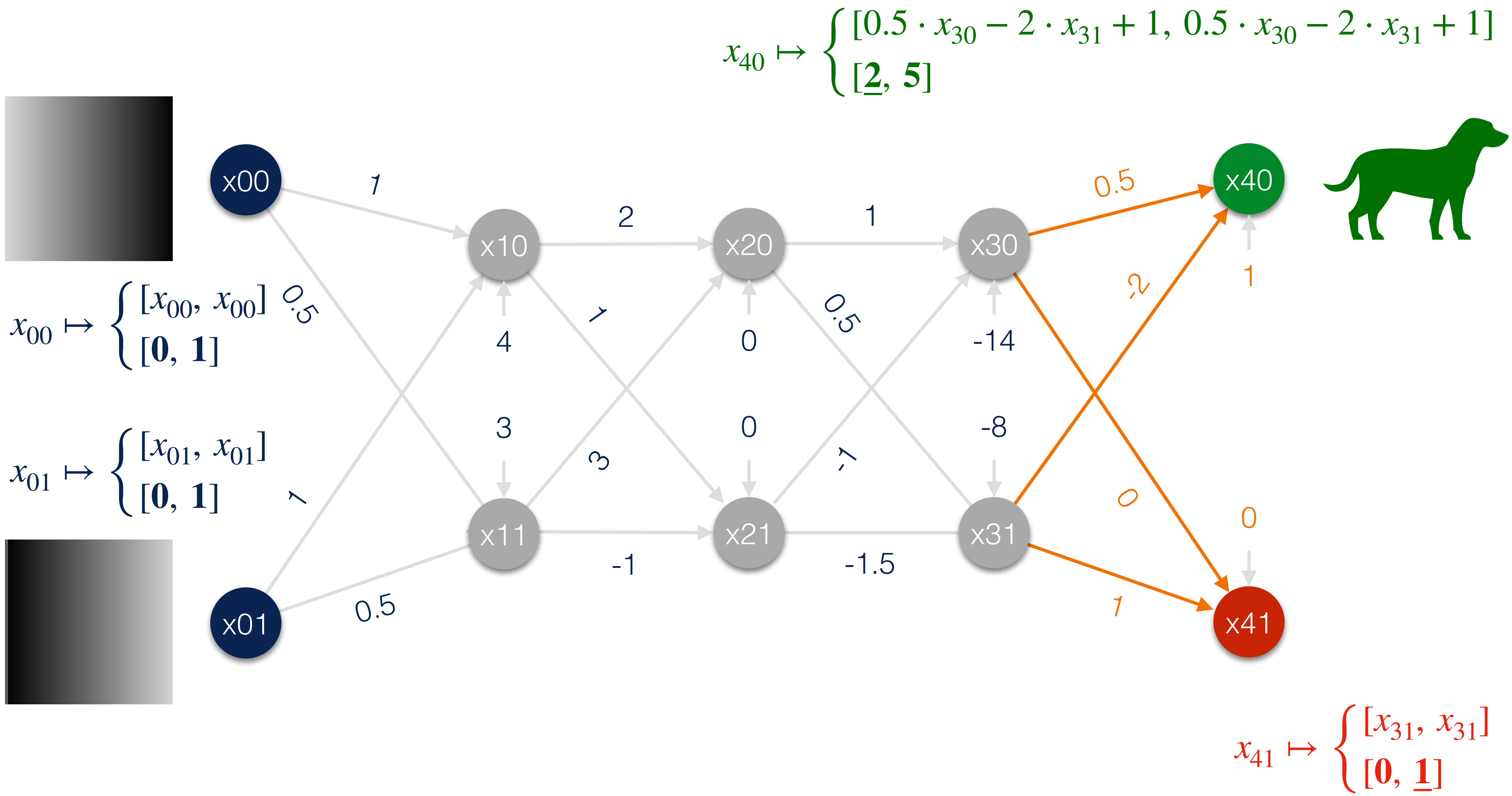
DeepPoly [Singh19]



Other Static Analysis Methods

- **T. Gehr, M. Mirman, D. Drachsler-Cohen, P. Tsankov, S. Chaudhuri, and M. Vechev**. *AI2: Safety and Robustness Certification of Neural Networks with Abstract Interpretation*. In S&P, 2018.
  the first use of abstract interpretation for verifying neural networks

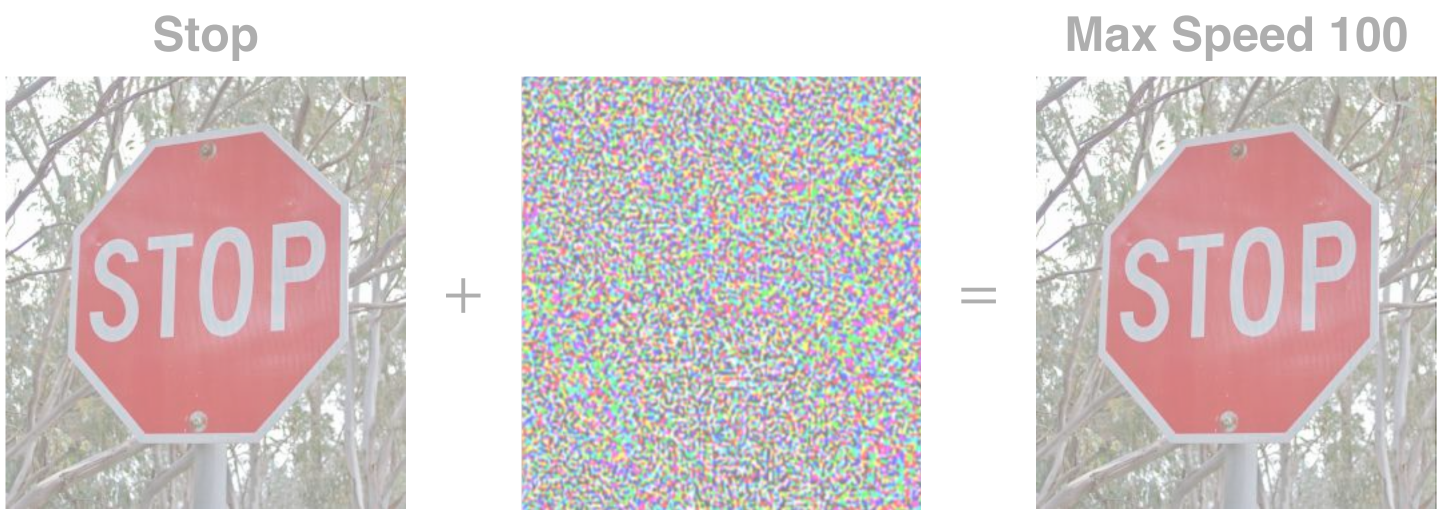
- **G. Singh, T. Gehr, M. Mirman, M. Püschel, and M. Vechev**. *Fast and Effective Robustness Certification*. In NeurIPS, 2018.
  a custom zonotope domain for certifying neural networks

- **G. Singh, R. Ganvir, M. Püschel, and M. Vechev**. *Beyond the Single Neuron Convex Barrier for Neural Network Certification*. In NeurIPS, 2019.
  a framework to jointly approximate k ReLU activations

- **M. N. Müller, G. Makarchuk, G. Singh, M. Püschel, and M. Vechev**. *PRIMA: General and Precise Neural Network Certification via Scalable Convex Hull Approximations*. In POPL, 2022.
  a multi-neuron abstraction via a convex-hull approximation algorithm

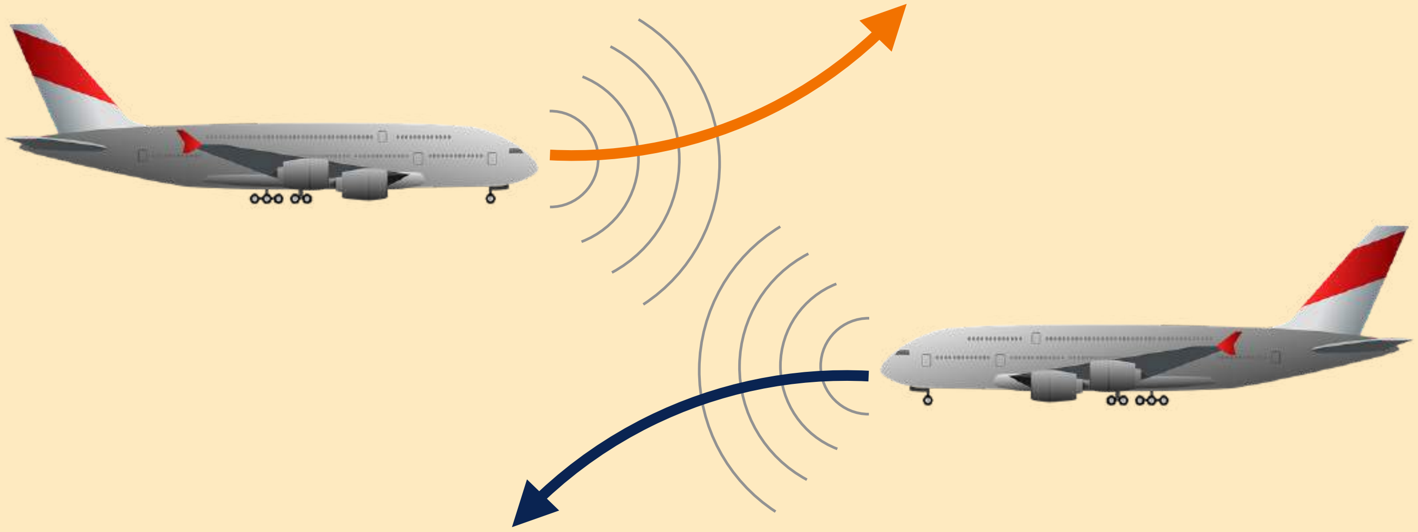
Stability

Goal G3 in [Kurd03]

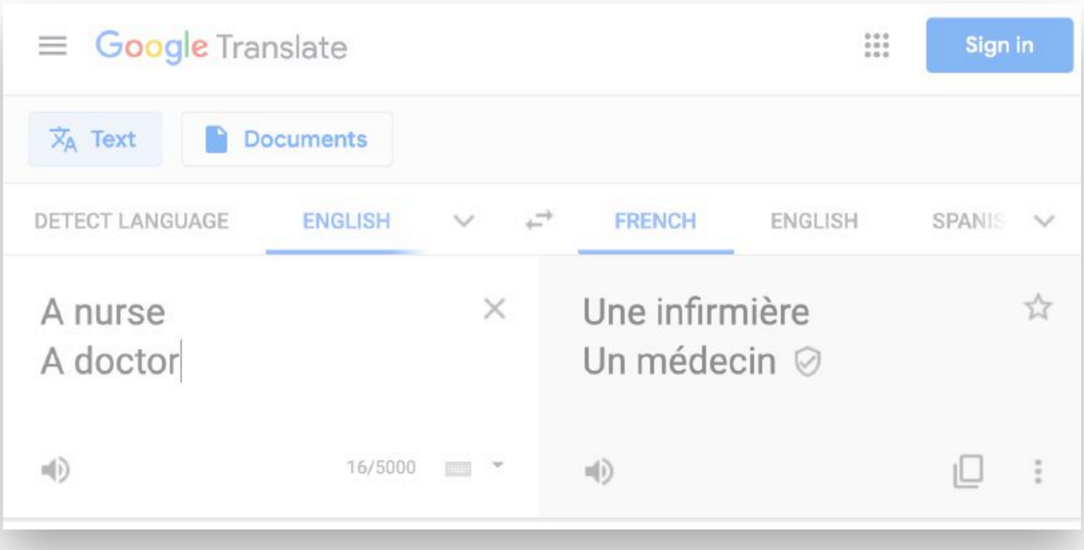


Safety

Goal G4 in [Kurd03]



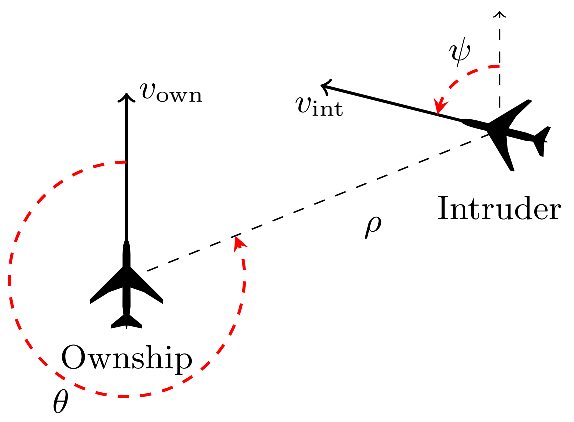
Fairness

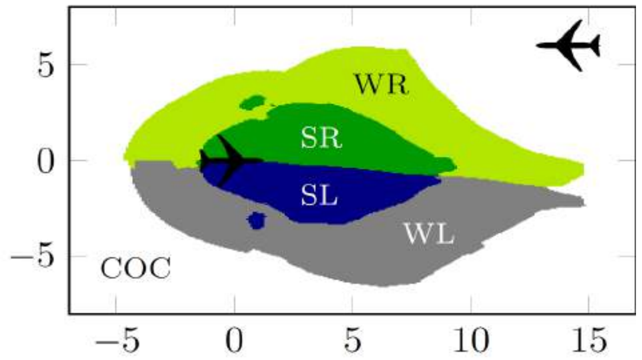


ACAS Xu [Julian16][Katz17]

Airborne Collision Avoidance System for Unmanned Aircraft

implemented using **45 feed-forward fully-connected ReLU networks**





5 input **sensor measurements**

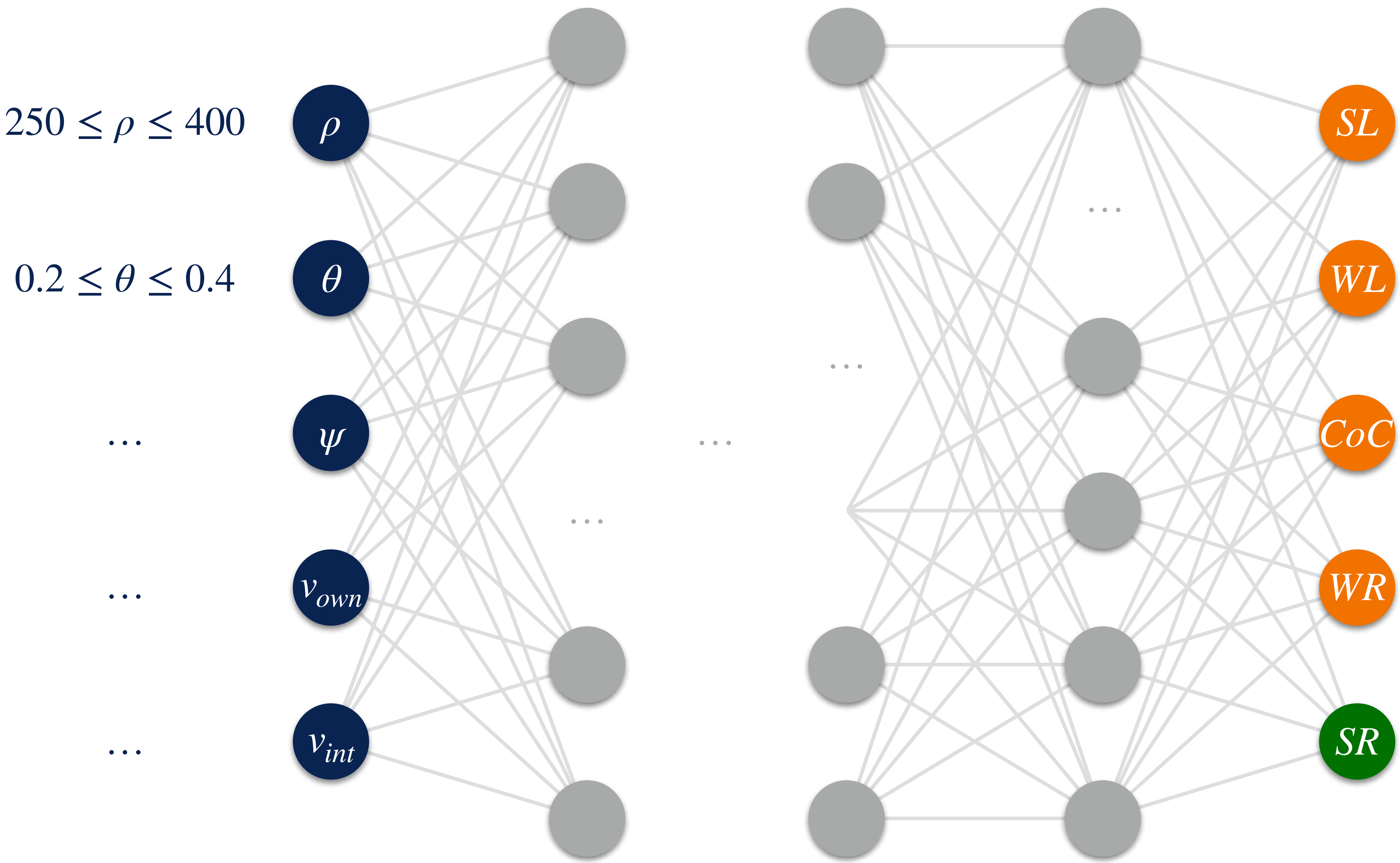
- ρ: distance from ownship to intruder
- θ: angle to intruder relative to ownship heading direction
- ψ: heading angle to intruder relative to ownship heading direction
- v_{own}: speed of ownship
- v_{int}: speed of intruder

5 output **horizontal advisories**

- Strong Left
- Weak Left
- Clear of Conflict
- Weak Right
- Strong Right

ACAS Xu Properties [Katz17]

Example: "if intruder is **near** and approaching **from the left**, go **Strong Right**"



Safety

Input-Output Properties

$\mathbf{I}$: input specification

$\mathbf{O}$: output specification

$$\mathcal{S}^{\mathbf{I}}_{\mathbf{O}} \stackrel{\text{def}}{=} \{[\![M]\!] \in \mathcal{P}(\Sigma^*) \mid \text{SAFE}^{\mathbf{I}}_{\mathbf{O}}([\![M]\!])\}$$

$\mathcal{S}^{\mathbf{I}}_{\mathbf{O}}$ is the set of all neural networks M (or, rather, their semantics $[\![M]\!]$) that **satisfy** the input and output specification $\mathbf{I}$ and $\mathbf{O}$

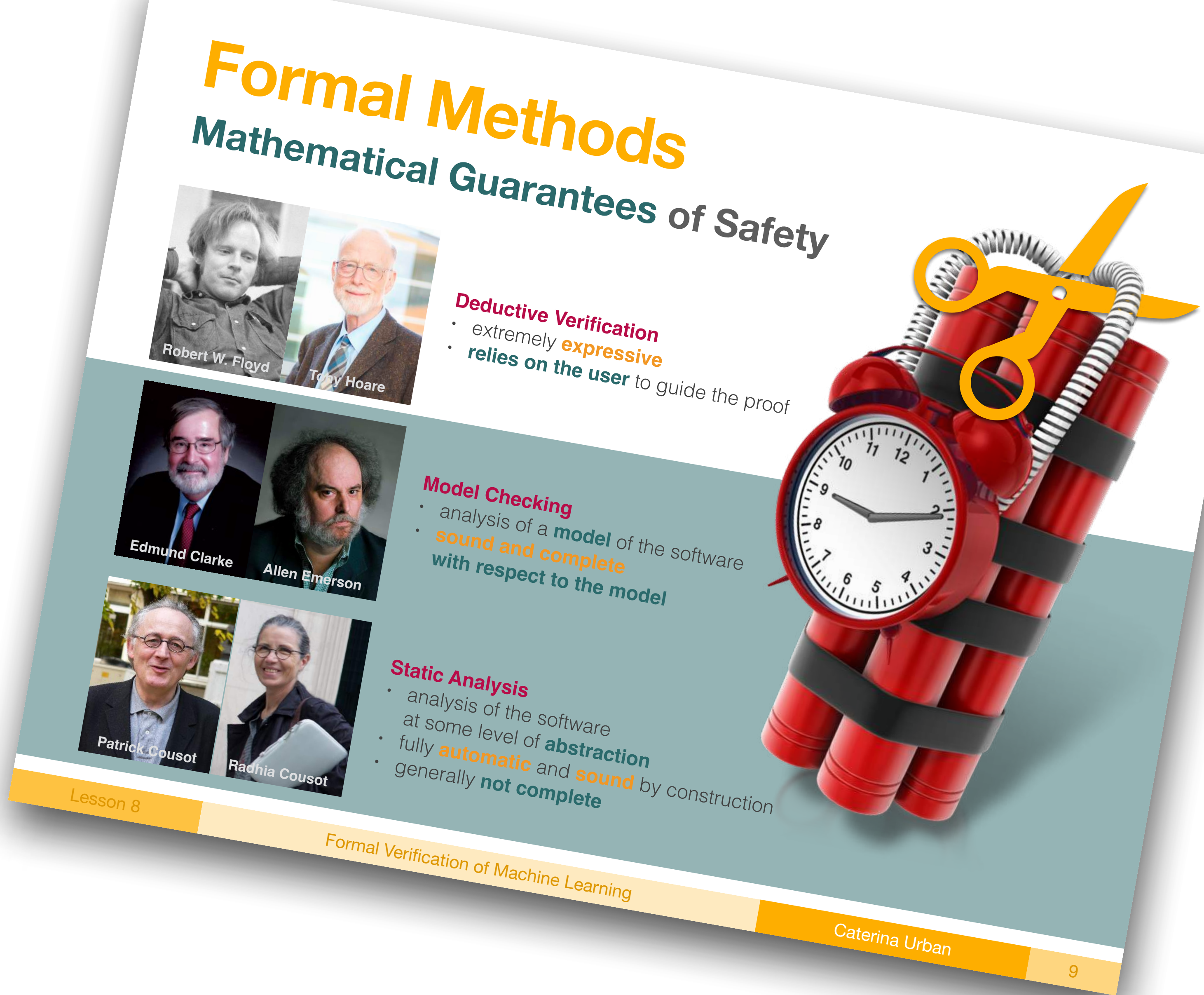
$$\text{SAFE}^{\mathbf{I}}_{\mathbf{O}}([\![M]\!]) \stackrel{\text{def}}{=} \forall t \in [\![M]\!] : t_0 \models \mathbf{I} \Rightarrow t_\omega \models \mathbf{O}$$

Theorem

$$M \models \mathcal{S}^{\mathbf{I}}_{\mathbf{O}} \Leftrightarrow \{[\![M]\!]\} \subseteq \mathcal{S}^{\mathbf{I}}_{\mathbf{O}}$$

Corollary

$$M \models \mathcal{S}^{\mathbf{I}}_{\mathbf{O}} \Leftrightarrow [\![M]\!] \subseteq \bigcup \mathcal{S}^{\mathbf{I}}_{\mathbf{O}}$$

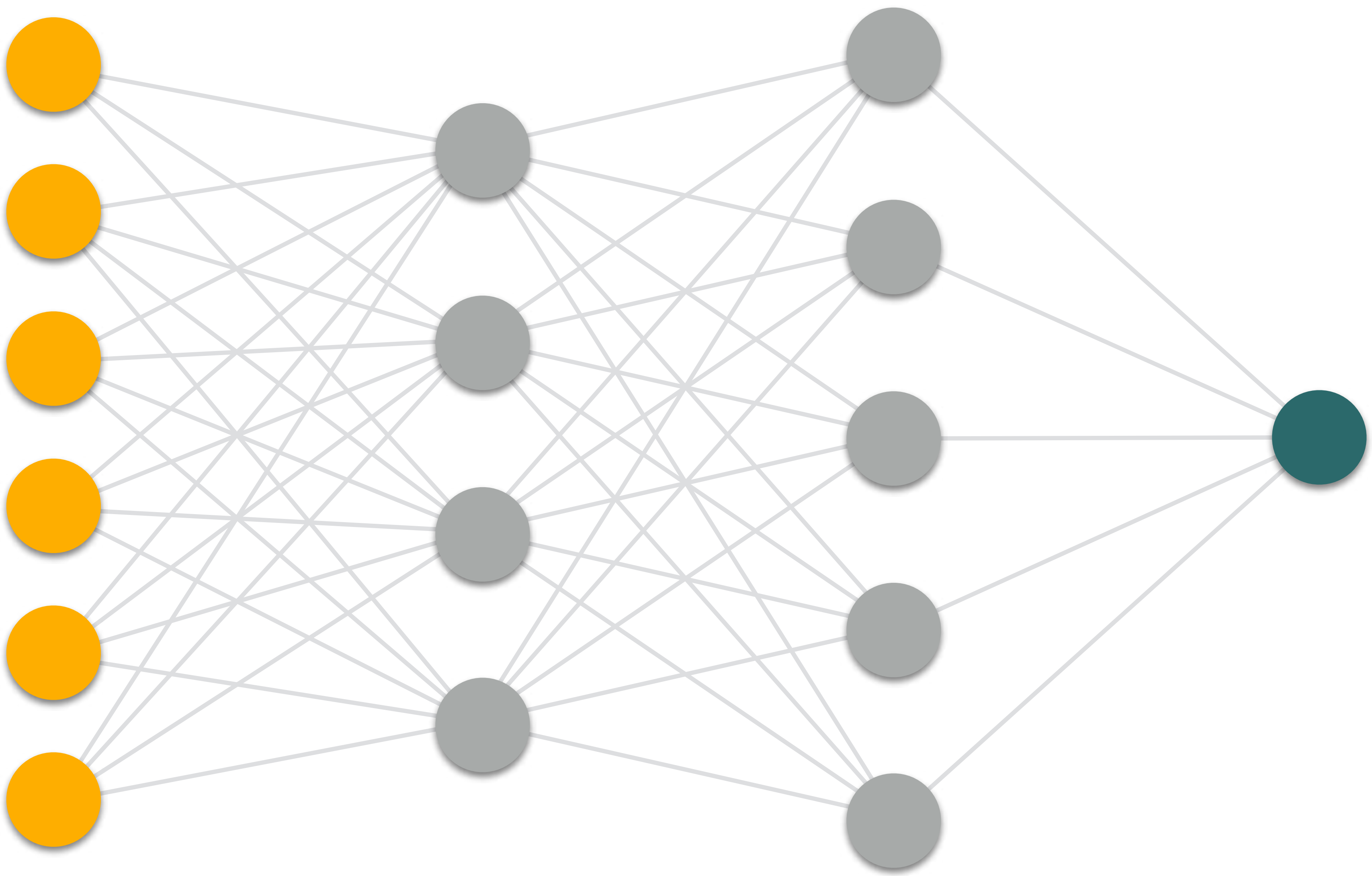


Model Checking Methods

Safety

Example

$l_j \leq x_{0,j} \leq u_j$



$x_N > 0$

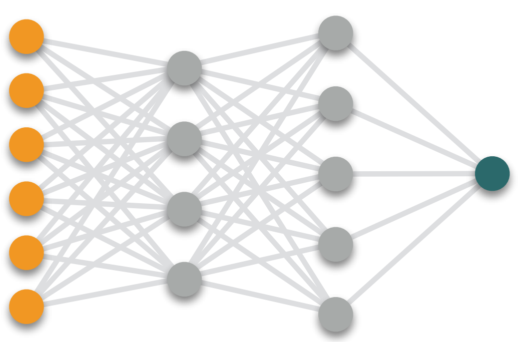
SMT-Based Methods

Verification Reduced to Constraint Satisfiability

$\mathbf{l_j \leq x_{0,j} \leq u_j}$ $\quad j \in \{0, \ldots, |\mathbf{X}_0|\}$ **input specification**

$$\hat{x}_{i+1,j} = \sum_{k=0}^{|\mathbf{X}_i|} w^i_{j,k} \cdot x_{i,k} + b_{i,j} \qquad i \in \{0, \ldots, n-1\}$$

$$x_{i,j} = \max\{0, \hat{x}_{i,j}\} \qquad i \in \{1, \ldots, n-1\}, \; j \in \{0, \ldots, |\mathbf{X}_i|\}$$



$\mathbf{x_N \leq 0}$ (negation of) **output specification**

satisfiable → ✗ **counterexample**

otherwise → ✓ **safe**

Planet

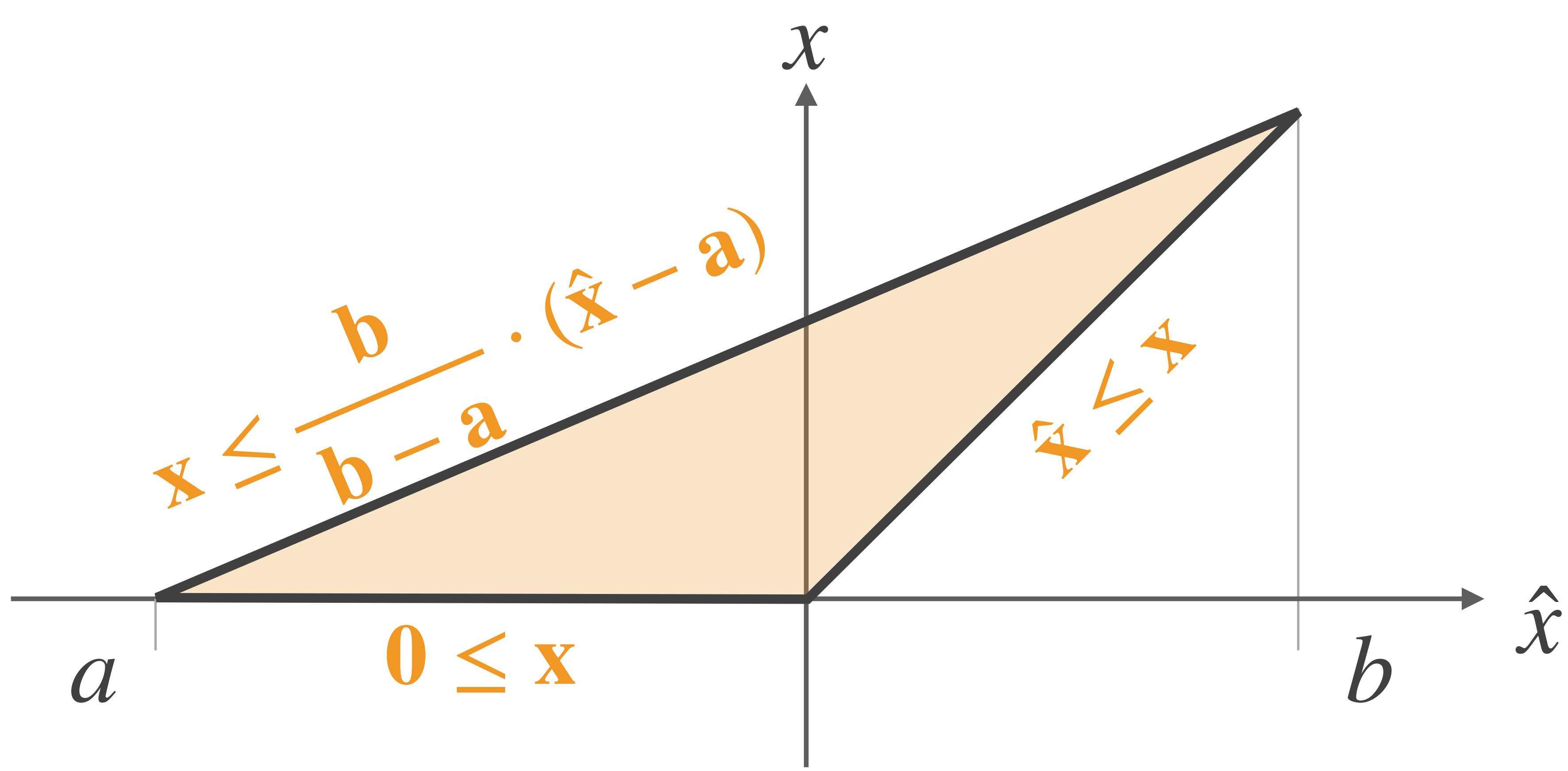
use **approximations** to reduce the solution search space

$$x_{i,j} = \max\{0, \hat{x}_{i,j}\}$$

$$\mathbf{0 \leq x_{i,j}}$$

$$\mathbf{\hat{x}_{i,j} \leq x_{i,j}}$$

$$\mathbf{x_{i,j} \leq \frac{b_{i,j}}{b_{i,j} - a_{i,j}} \cdot (\hat{x}_{i,j} - a_{i,j})}$$



R. Ehlers - Formal Verification of Piece-Wise Linear Feed-Forward Neural Networks (ATVA 2017)

Reluplex

based on the **simplex algorithm** extended to support ReLUs

Variable	Value
$\mathbf{x_{00}}$	v_{00}
$\dots$	$\dots$
$\mathbf{\hat{x}_{ij}}$	$\hat{v}_{ij}$
$\mathbf{x_{ij}}$	v_{ij}
$\dots$	$\dots$
$\mathbf{x_N}$	v_N

Variable	Value
$\mathbf{x_{00}}$	v_{00}
$\dots$	$\dots$
$\mathbf{\hat{x}_{ij}}$	$\hat{v}'_{ij}$
$\mathbf{x_{ij}}$	v_{ij}
$\dots$	$\dots$
$\mathbf{x_N}$	v_N

Variable	Value
$\mathbf{x_{00}}$	v_{00}
$\dots$	$\dots$
$\mathbf{\hat{x}_{ij}}$	$\hat{v}'_{ij}$
$\mathbf{x_{ij}}$	$\hat{v}'_{ij}$
$\dots$	$\dots$
$\mathbf{x_N}$	v_N

Variable	Value
$\mathbf{x_{00}}$	v_{00}
$\dots$	$\dots$
$\mathbf{\hat{x}_{ij}}$	$\hat{v}'_{ij}$
$\mathbf{x_{ij}}$	0
$\dots$	$\dots$
$\mathbf{x_N}$	v_N

G. Katz et al. - Reluplex: An Efficient SMT Solver for Verifying Deep Neural Networks (CAV 2017)

Reluplex

based on th
extended

Follow-up Work

G. Katz et al. - The Marabou Framework for Verification and Analysis of Deep Neural Networks (CAV 2019)

Variable	Value
$\mathbf{x}_{00}$	v_{00}
$\dots$	$\dots$
$\hat{\mathbf{x}}_{ij}$	$\hat{v}_{ij}$
$\mathbf{x}_{ij}$	v_{ij}
$\dots$	$\dots$
$\mathbf{x}_N$	v_N

Variable	Value
$\mathbf{x}_{00}$	v_{00}
$\dots$	$\dots$
$\hat{\mathbf{x}}_{ij}$	$\hat{v}'_{ij}$
$\mathbf{x}_{ij}$	v_{ij}
$\dots$	$\dots$
$\mathbf{x}_N$	v_N

Variable	
$\mathbf{x}_{00}$	v_{00}
$\dots$	$\dots$
$\hat{\mathbf{x}}_{ij}$	$\hat{v}'_{ij}$
$\mathbf{x}_{ij}$	$\hat{v}'_{ij}$
$\dots$	$\dots$
$\mathbf{x}_N$	v_N

Variable	Value
$\mathbf{x}_{00}$	v_{00}
$\dots$	$\dots$
$\hat{\mathbf{x}}_{ij}$	$\hat{v}'_{ij}$
$\mathbf{x}_{ij}$	0
$\dots$	$\dots$
$\mathbf{x}_N$	v_N

G. Katz et al. - Reluplex: An Efficient SMT Solver for Verifying Deep Neural Networks (CAV 2017)

Other SMT-Based Methods

- **L. Pulina and A. Tacchella**. *An Abstraction-Refinement Approach to Verification of Artificial Neural Networks*. In CAV, 2010.
  the first formal verification method for neural networks

- **O. Bastani, Y. Ioannou, L. Lampropoulos, D. Vytiniotis, A. Nori, and A. Criminisi**. *Measuring Neural Net Robustness with Constraints*. In NeurIPS, 2016.
  an approach for finding the nearest adversarial example according to the L_∞ distance

- **X. Huang, M. Kwiatkowska, S. Wang, and M. Wu**. *Safety Verification of Deep Neural Networks*. In CAV, 2017.
  an approach for proving local robustness to adversarial perturbations

- **N. Narodytska, S. Kasiviswanathan, L. Ryzhyk, M. Sagiv, and T. Walsh**. *Verifying Properties of Binarized Deep Neural Networks*. In AAAI, 2018.
  C. H. Cheng, G. Nührenberg, C. H. Huang, and H. Ruess. *Verification of Binarized Neural Networks via Inter-Neuron Factoring*. In VSTTE, 2018.
  approaches focusing on binarized neural networks

MILP-Based Methods

Verification Reduced to Mixed Integer Linear Program

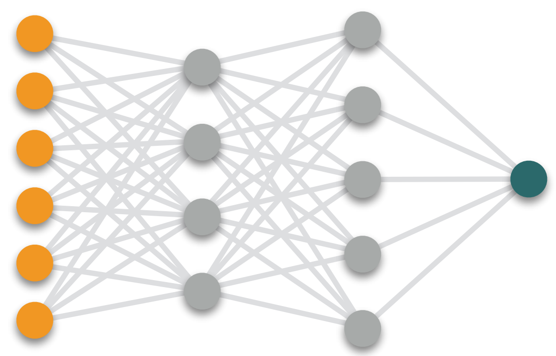
$\mathbf{l_j} \leq \mathbf{x_{0,j}} \leq \mathbf{u_j}$ $\quad j \in \{0, \ldots, |\mathbf{X}_0|\}$ **input specification**

$$\hat{x}_{i+1,j} = \sum_{k=0}^{|\mathbf{X}_i|} w_{j,k}^{i} \cdot x_{i,k} + b_{i,j} \qquad i \in \{0, \ldots, n-1\}$$

$$x_{i,j} = \delta_{\mathbf{i,j}} \cdot \hat{x}_{i,j} \qquad \delta_{\mathbf{i,j}} \in \{\mathbf{0}, \mathbf{1}\}$$

$$\delta_{\mathbf{i,j}} = 1 \Rightarrow \hat{x}_{i,j} \geq 0 \qquad i \in \{1, \ldots, n-1\}$$

$$\delta_{\mathbf{i,j}} = 0 \Rightarrow \hat{x}_{i,j} < 0 \qquad j \in \{0, \ldots, |\mathbf{X}_i|\}$$



min $\mathbf{x_N}$ **objective function**

min $\mathbf{x_N} \leq \mathbf{0} \rightarrow$ ✗ **counterexample**

otherwise $\rightarrow$ ✓ **safe**

MILP-Based Methods

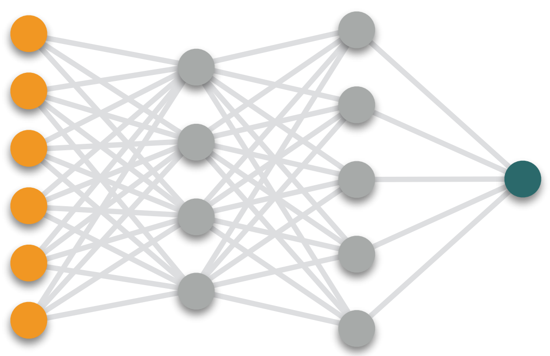
Bounded Encoding with Symmetric Bounds

$$\hat{x}_{i+1,j} = \sum_{k=0}^{|\mathbf{X}_i|} w^i_{j,k} \cdot x_{i,k} + b_{i,j} \qquad i \in \{0, \ldots, n-1\}$$

$$0 \leq x_{i,j} \leq \mathbf{M_{i,j}} \cdot \delta_{i,j} \qquad \delta_{\mathbf{i,j}} \in \{\mathbf{0}, \mathbf{1}\}$$

$$\hat{x}_{i,j} \leq x_{i,j} \leq \hat{x}_{i,j} - \mathbf{M_{i,j}} \cdot (1 - \delta_{i,j}) \qquad i \in \{1, \ldots, n-1\}$$

$$\mathbf{M_{i,j}} = \mathbf{max}\{-\mathbf{l_i}, \mathbf{u_i}\} \qquad j \in \{0, \ldots, |\mathbf{X}_i|\}$$



Sherlock

Output Range Analysis

use **local search** to speed up the MILP solver

$\mathbf{l_j \leq x_{0,j} \leq u_j}$

$$\hat{x}_{i+1,j} = \sum_{k=0}^{|\mathbf{X}_i|} w^i_{j,k} \cdot x_{i,k} + b_{i,j}$$

$$0 \leq x_{i,j} \leq \mathbf{M_{i,j}} \cdot \delta_{i,j}$$

$$\hat{x}_{i,j} \leq x_{i,j} \leq \hat{x}_{i,j} - \mathbf{M_{i,j}} \cdot (1 - \delta_{i,j})$$

$$\mathbf{M_{i,j} = \max\{-l_i, u_i\}}$$

$\mathbf{\min\ x_N}$

S. Dutta et al. - Output Range Analysis for Deep Feedforward Neural Networks (NFM 2018)

Sherlock

Output Range Analysis

use **local search** to speed up the MILP solver

$$\mathbf{l_j} \leq \mathbf{x_{0,j}} \leq \mathbf{u_j}$$

$$\hat{x}_{i+1,j} = \sum_{k=0}^{|\mathbf{X}_i|} w^i_{j,k} \cdot x_{i,k} + b_{i,j}$$

$$0 \leq x_{i,j} \leq \mathbf{M_{i,j}} \cdot \delta_{i,j}$$

$$\hat{x}_{i,j} \leq x_{i,j} \leq \hat{x}_{i,j} - \mathbf{M_{i,j}} \cdot (1 - \delta_{i,j})$$

$$\mathbf{M_{i,j}} = \mathbf{max}\{-\mathbf{l_i}, \mathbf{u_i}\}$$

$$\mathbf{x_N} < \mathbf{L}$$

sample random input $\mathbf{X}$ and evaluate output $\mathbf{L}$

S. Dutta et al. - Output Range Analysis for Deep Feedforward Neural Networks (NFM 2018)

Sherlock

Output Range Analysis

use **local search** to speed up the MILP solver

$\mathbf{l_j \leq x_{0,j} \leq u_j}$

$$\hat{x}_{i+1,j} = \sum_{k=0}^{|\mathbf{X}_i|} w^i_{j,k} \cdot x_{i,k} + b_{i,j}$$

$$0 \leq x_{i,j} \leq \mathbf{M_{i,j}} \cdot \delta_{i,j}$$

$$\hat{x}_{i,j} \leq x_{i,j} \leq \hat{x}_{i,j} - \mathbf{M_{i,j}} \cdot (1 - \delta_{i,j})$$

$$\mathbf{M_{i,j}} = \mathbf{max}\{-\mathbf{l_i}, \mathbf{u_i}\}$$

$\mathbf{x_N} < \mathbf{L}$

find another input $\hat{\mathbf{X}}$ such that $\hat{\mathbf{L}} \leq \mathbf{x_N}$

S. Dutta et al. - Output Range Analysis for Deep Feedforward Neural Networks (NFM 2018)

Sherlock

Output Range Analysis

use **local search** to speed up the MILP solver

$$\mathbf{l_j \leq x_{0,j} \leq u_j}$$

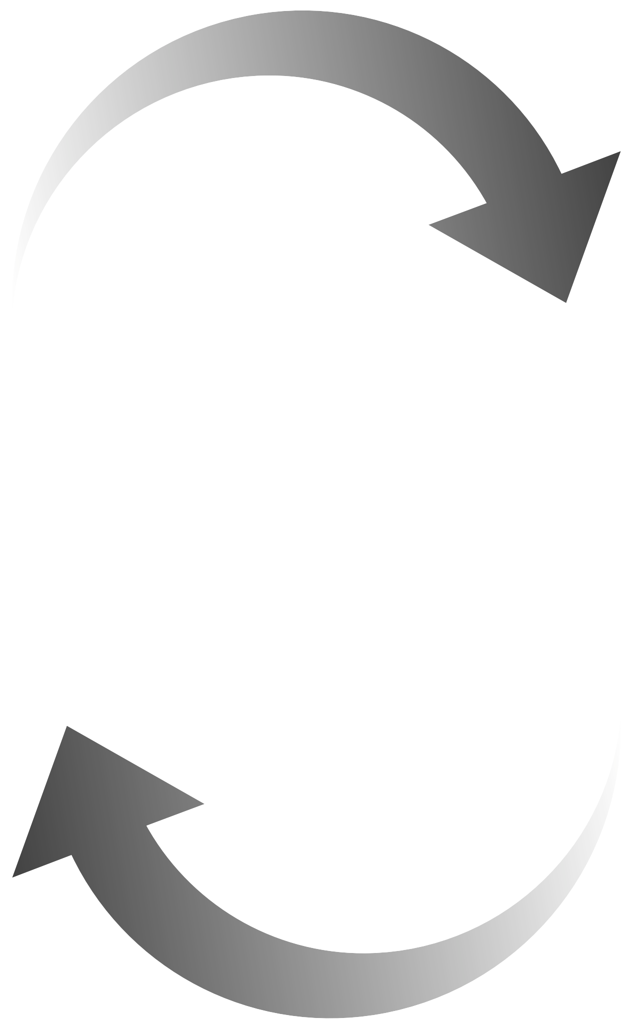
$$\hat{x}_{i+1,j} = \sum_{k=0}^{|\mathbf{X}_i|} w^i_{j,k} \cdot x_{i,k} + b_{i,j}$$

$$0 \leq x_{i,j} \leq \mathbf{M_{i,j}} \cdot \delta_{i,j}$$

$$\hat{x}_{i,j} \leq x_{i,j} \leq \hat{x}_{i,j} - \mathbf{M_{i,j}} \cdot (1 - \delta_{i,j})$$

$$\mathbf{M_{i,j}} = \mathbf{max}\{-\mathbf{l_i}, \mathbf{u_i}\}$$

$$\mathbf{x_N} < \hat{\mathbf{L}}$$



find another input $\hat{\mathbf{X}}$ such that $\hat{\mathbf{L}} \leq \mathbf{x_N}$

S. Dutta et al. - Output Range Analysis for Deep Feedforward Neural Networks (NFM 2018)

MILP-Based Methods

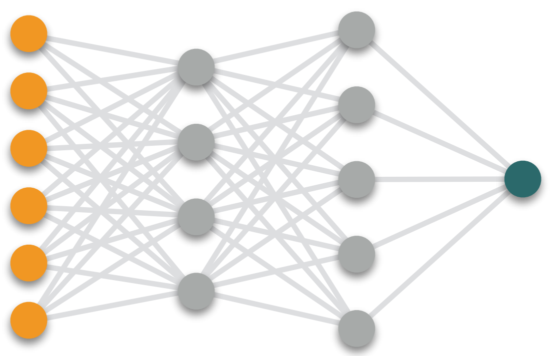
Bounded Encoding with Asymmetric Bounds

$$\hat{x}_{i+1,j} = \sum_{k=0}^{|\mathbf{X}_i|} w^i_{j,k} \cdot x_{i,k} + b_{i,j} \qquad i \in \{0,\ldots,n-1\}$$

$$\delta_{\mathbf{i,j}} \in \{\mathbf{0},\mathbf{1}\}$$

$$0 \leq x_{i,j} \leq \mathbf{u_{i,j}} \cdot \delta_{i,j} \qquad i \in \{1,\ldots,n-1\}$$

$$\hat{x}_{i,j} \leq x_{i,j} \leq \hat{x}_{i,j} - \mathbf{l_{i,j}} \cdot (1 - \delta_{i,j}) \qquad j \in \{0,\ldots,|\,\mathbf{X}_i\,|\}$$



MIPVerify

Finding Nearest Adversarial Example

$\min_{\mathbf{X}'} \mathbf{d}(\mathbf{X}, \mathbf{X}')$

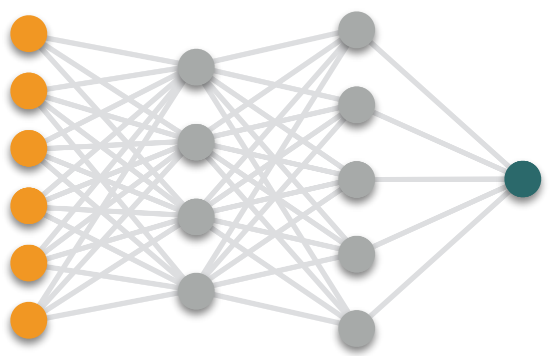
$$\hat{x}_{i+1,j} = \sum_{k=0}^{|\mathbf{X}_i|} w^i_{j,k} \cdot x_{i,k} + b_{i,j} \qquad i \in \{0, \ldots, n-1\}$$

$$\delta_{\mathbf{i,j}} \in \{\mathbf{0}, \mathbf{1}\}$$

$$0 \leq x_{i,j} \leq \mathbf{u_{i,j}} \cdot \delta_{i,j} \qquad i \in \{1, \ldots, n-1\}$$

$$\hat{x}_{i,j} \leq x_{i,j} \leq \hat{x}_{i,j} - \mathbf{l_{i,j}} \cdot (1 - \delta_{i,j}) \qquad j \in \{0, \ldots, |\mathbf{X}_i|\}$$

$$\mathbf{x_N} \neq \mathbf{O}$$



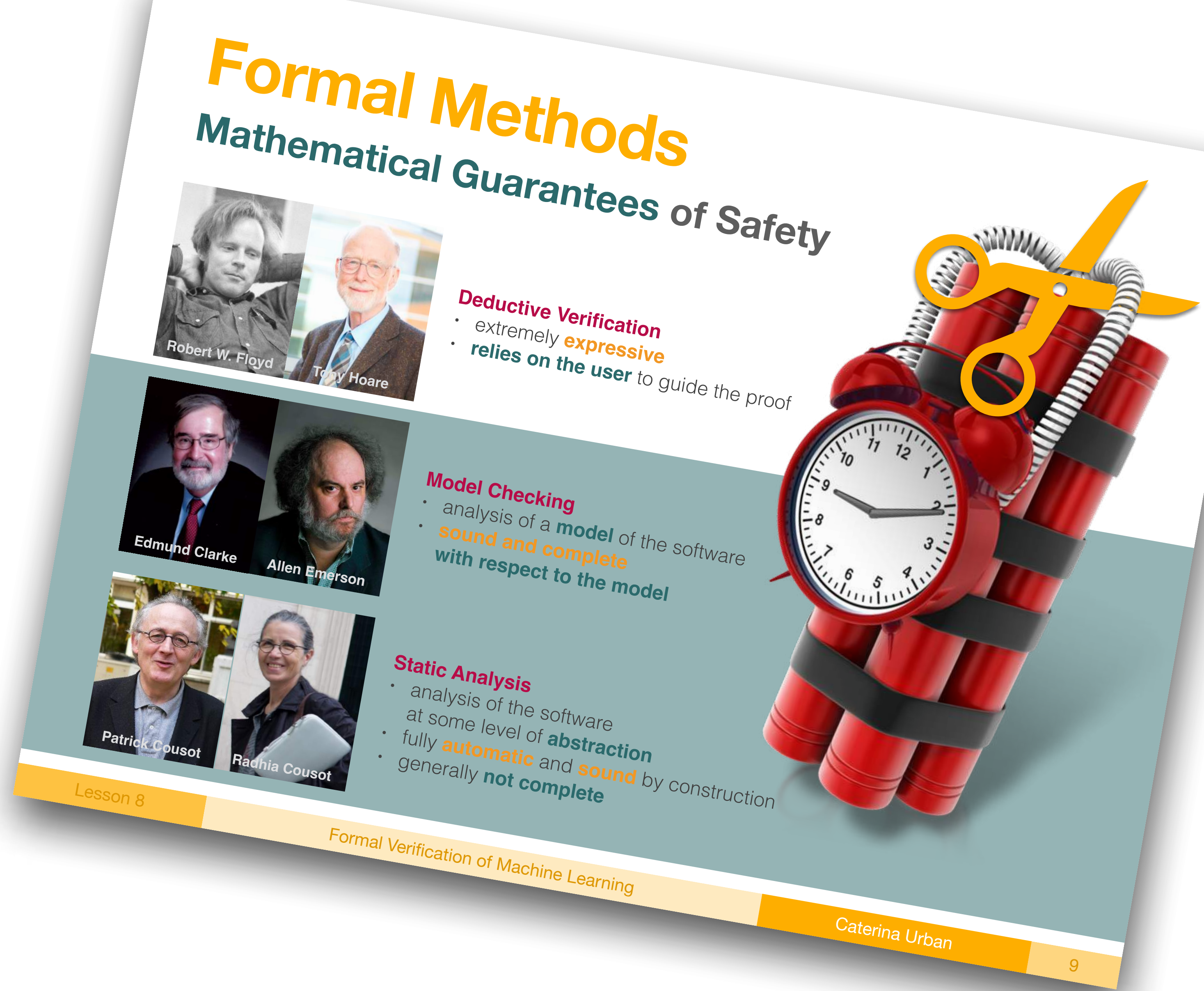
V. Tjeng et al. - Evaluating Robustness of Neural Networks with Mixed Integer Programming (ICLR 2019)

Other MILP-Based Methods

- **R. Bunel, I. Turkaslan, P. H. S. Torr, P. Kohli, and M. P. Kumar**. *A Unified View of Piecewise Linear Neural Network Verification*. In NeurIPS, 2018.
  a unifying verification framework for piecewise-linear ReLU neural networks

- **C.-H. Cheng, G. Nührenberg, and H. Ruess**. *Maximum Resilience of Artificial Neural Networks*. In ATVA, 2017.
  an approach for finding a lower bound on robustness to adversarial perturbations

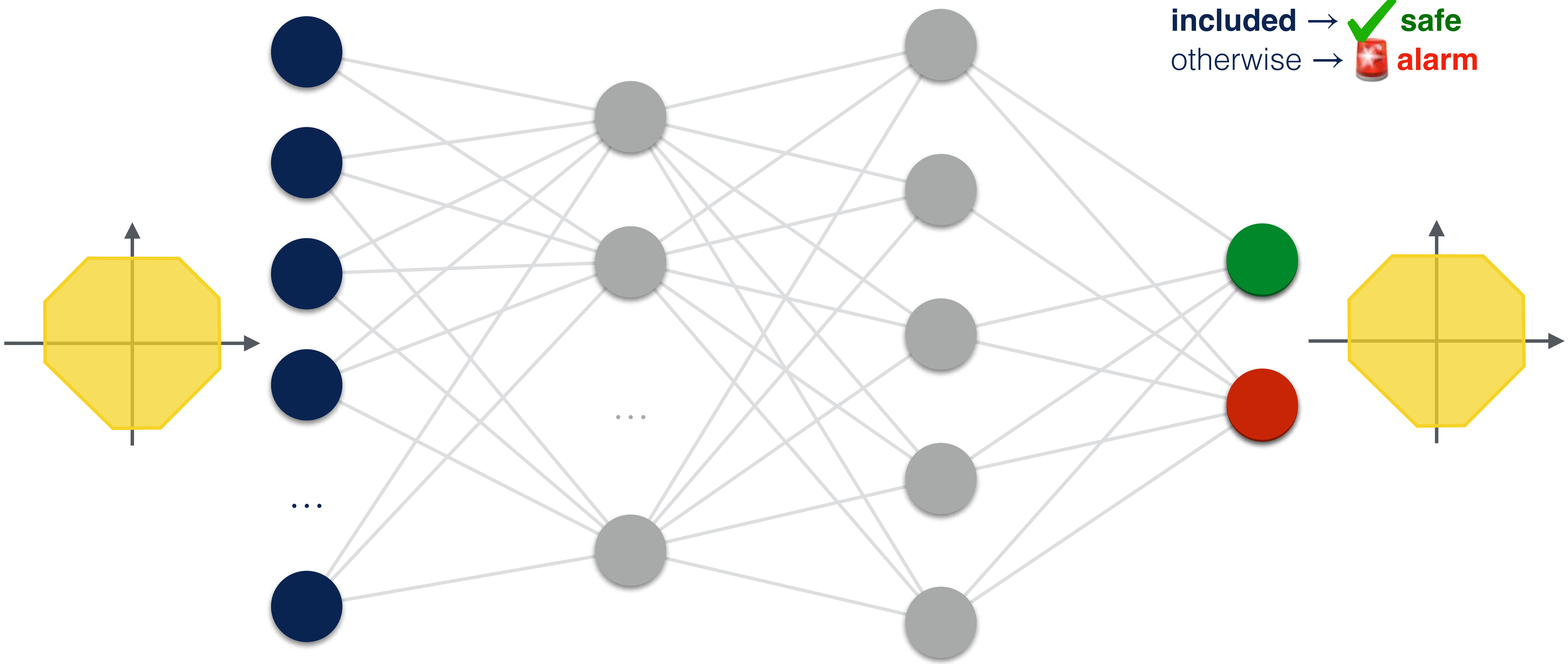
- **M. Fischetti and J. Jo**. *Deep Neural Networks and Mixed Integer Linear Optimization*. 2018.
  an approach for feature visualization and building adversarial examples



Static Analysis Methods

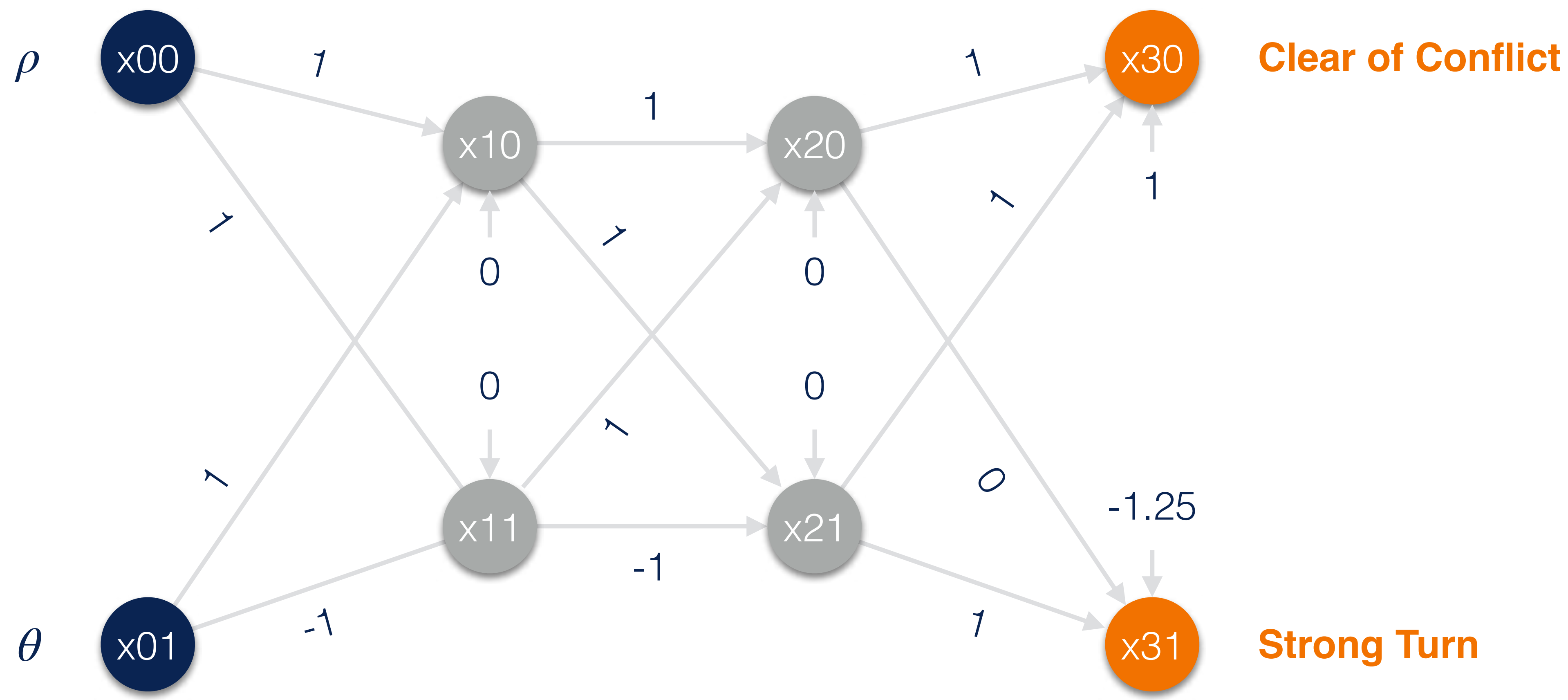
Forward Analysis

② check output for **inclusion** in **output specification $\mathbf{O}$**:
included → ✔ **safe**
otherwise → 🚨 **alarm**



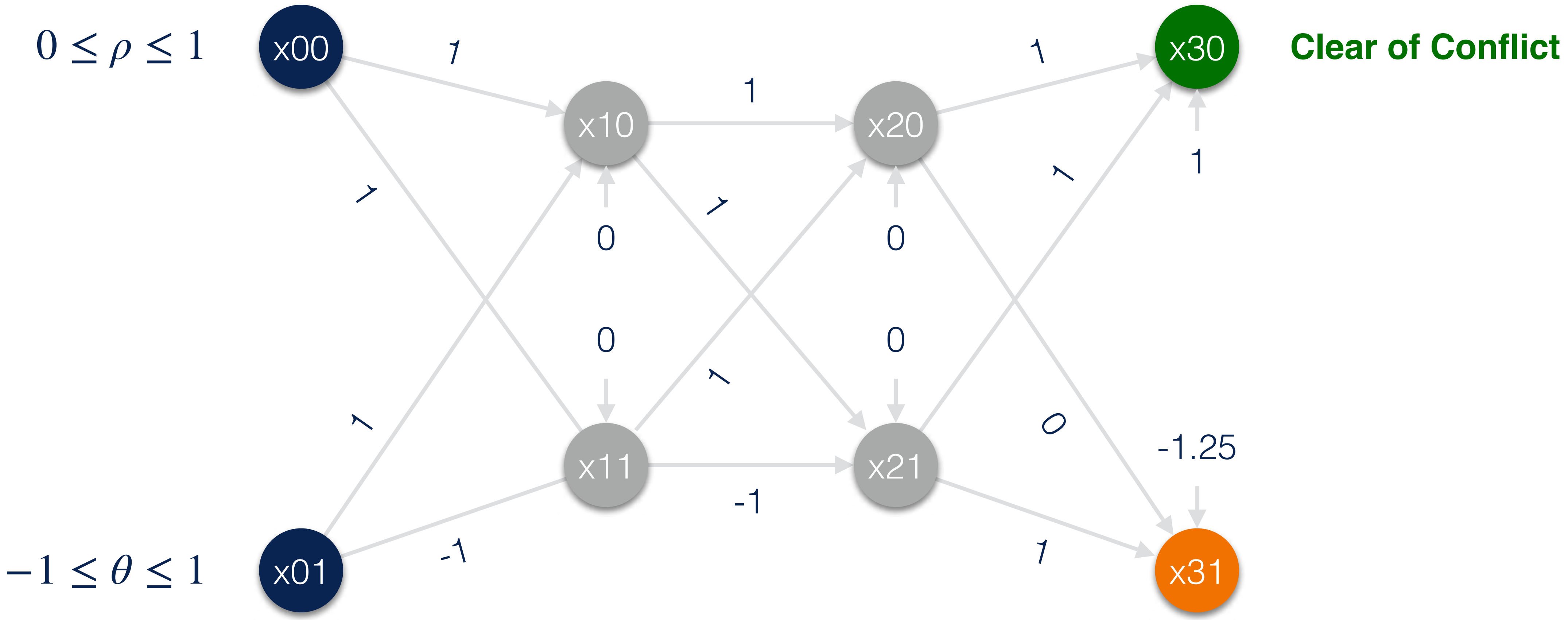
① proceed **forwards from an abstraction** of the input specification $\mathbf{I}$

Example



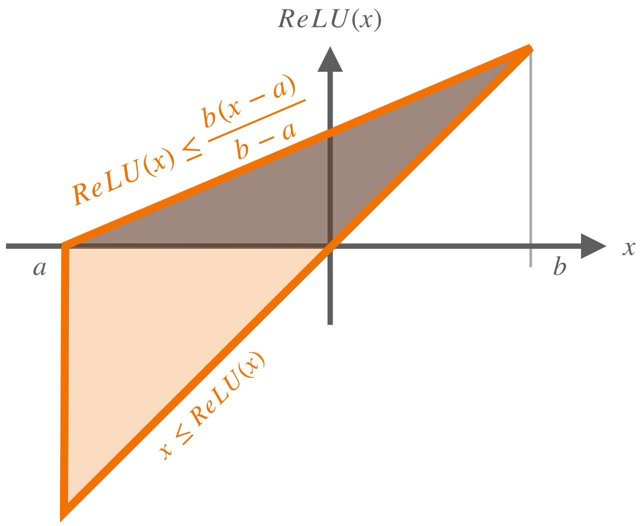
ρ
θ
x00
x01
x10
x11
x20
x21
x30
x31
1
1
1
1
-1
0
0
1
1
-1
1
0
0
1
1
0
1
-1.25
Clear of Conflict
Strong Turn

Example



$0 \leq \rho \leq 1$
$-1 \leq \theta \leq 1$
x00
x01
x10
x11
x20
x21
x30
x31
Clear of Conflict
1
1
1
-1
1
0
0
1
-1
1
1
0
0
1
1
1
0
1
-1.25

DeepPoly Domain [Singh19]



$$x_{10} \mapsto \begin{cases} [x_{10},\ \frac{2}{3} \cdot x_{10} + \frac{2}{3}] \\ [\mathbf{-1},\ \mathbf{2}] \end{cases}$$

ReLU

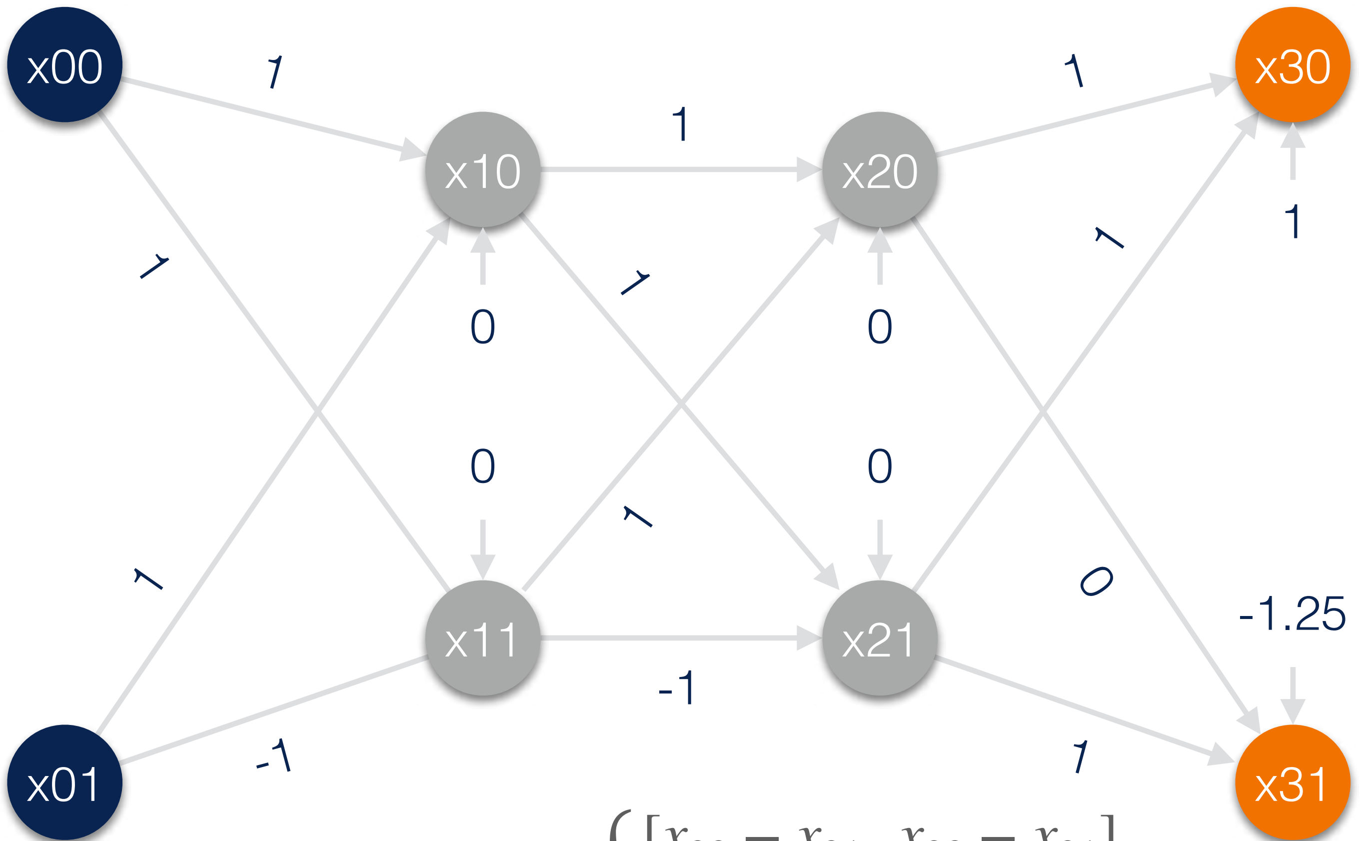
$$x_{10} \mapsto \begin{cases} [x_{00} + x_{01},\ x_{00} + x_{01}] \\ [\mathbf{-1},\ \mathbf{2}] \end{cases}$$

$0 \leq \rho \leq 1$

$$x_{00} \mapsto \begin{cases} [x_{00},\ x_{00}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{01} \mapsto \begin{cases} [x_{01},\ x_{01}] \\ [\mathbf{-1},\ \mathbf{1}] \end{cases}$$

$-1 \leq \theta \leq 1$



Clear of Conflict

Strong Turn

$$x_{11} \mapsto \begin{cases} [x_{00} - x_{01},\ x_{00} - x_{01}] \\ [\mathbf{-1},\ \mathbf{2}] \end{cases}$$

ReLU

$$x_{11} \mapsto \begin{cases} [x_{11},\ \frac{2}{3} \cdot x_{11} + \frac{2}{3}] \\ [\mathbf{-1},\ \mathbf{2}] \end{cases}$$

DeepPoly Domain [Singh19]

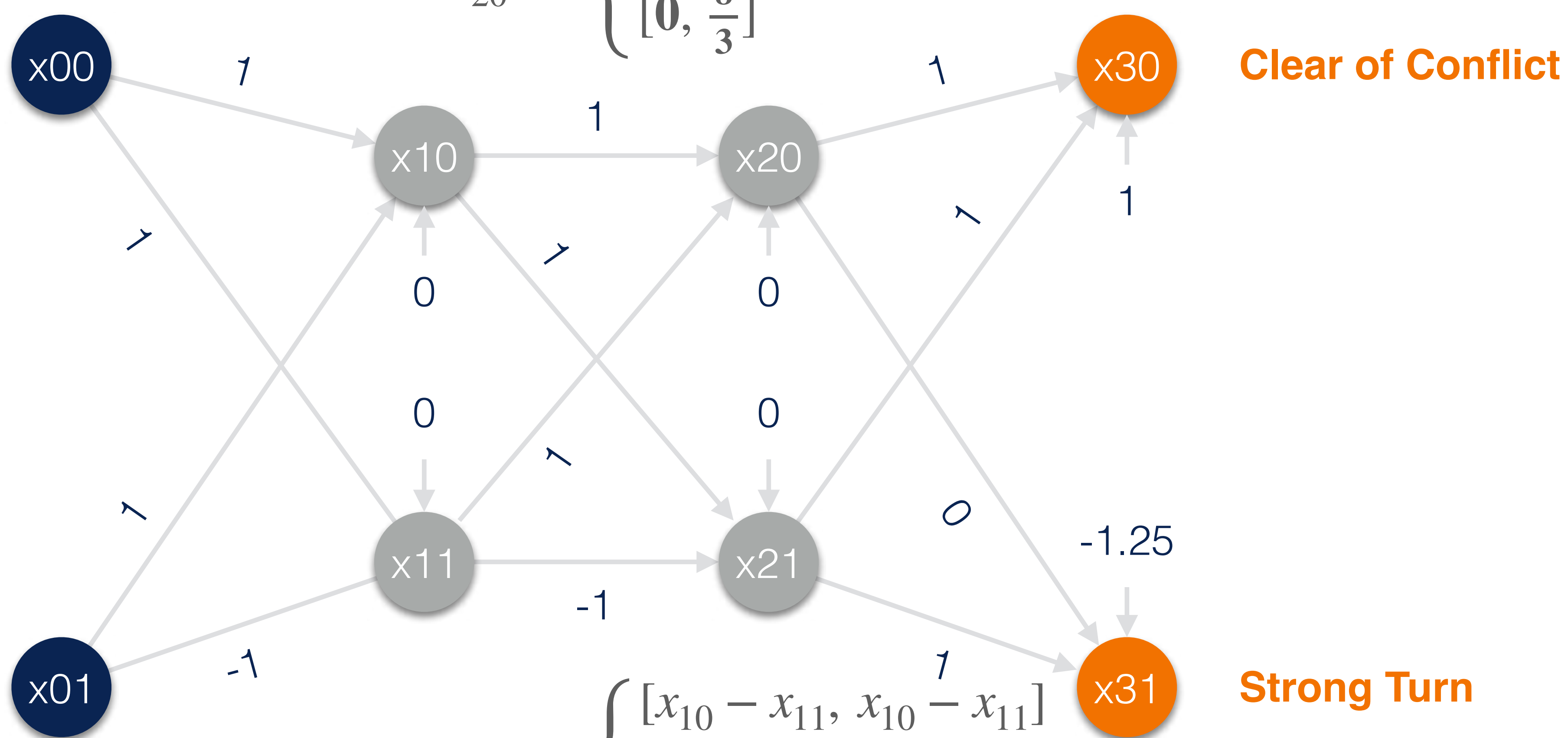
$$x_{20} \mapsto \begin{cases} [x_{10} + x_{11},\ x_{10} + x_{11}] \\ [\mathbf{0},\ \frac{\mathbf{8}}{\mathbf{3}}] \end{cases}$$

$0 \le \rho \le 1$

$$x_{00} \mapsto \begin{cases} [x_{00},\ x_{00}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{01} \mapsto \begin{cases} [x_{01},\ x_{01}] \\ [\mathbf{-1},\ \mathbf{1}] \end{cases}$$

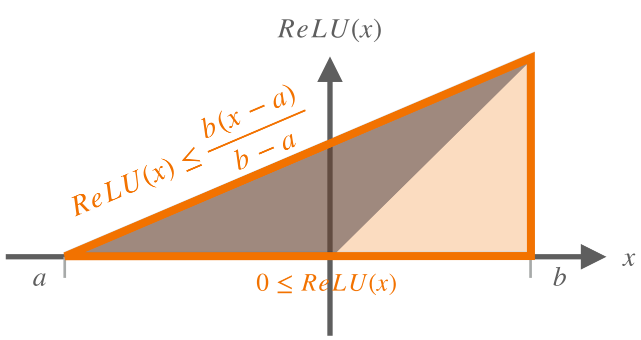
$-1 \le \theta \le 1$



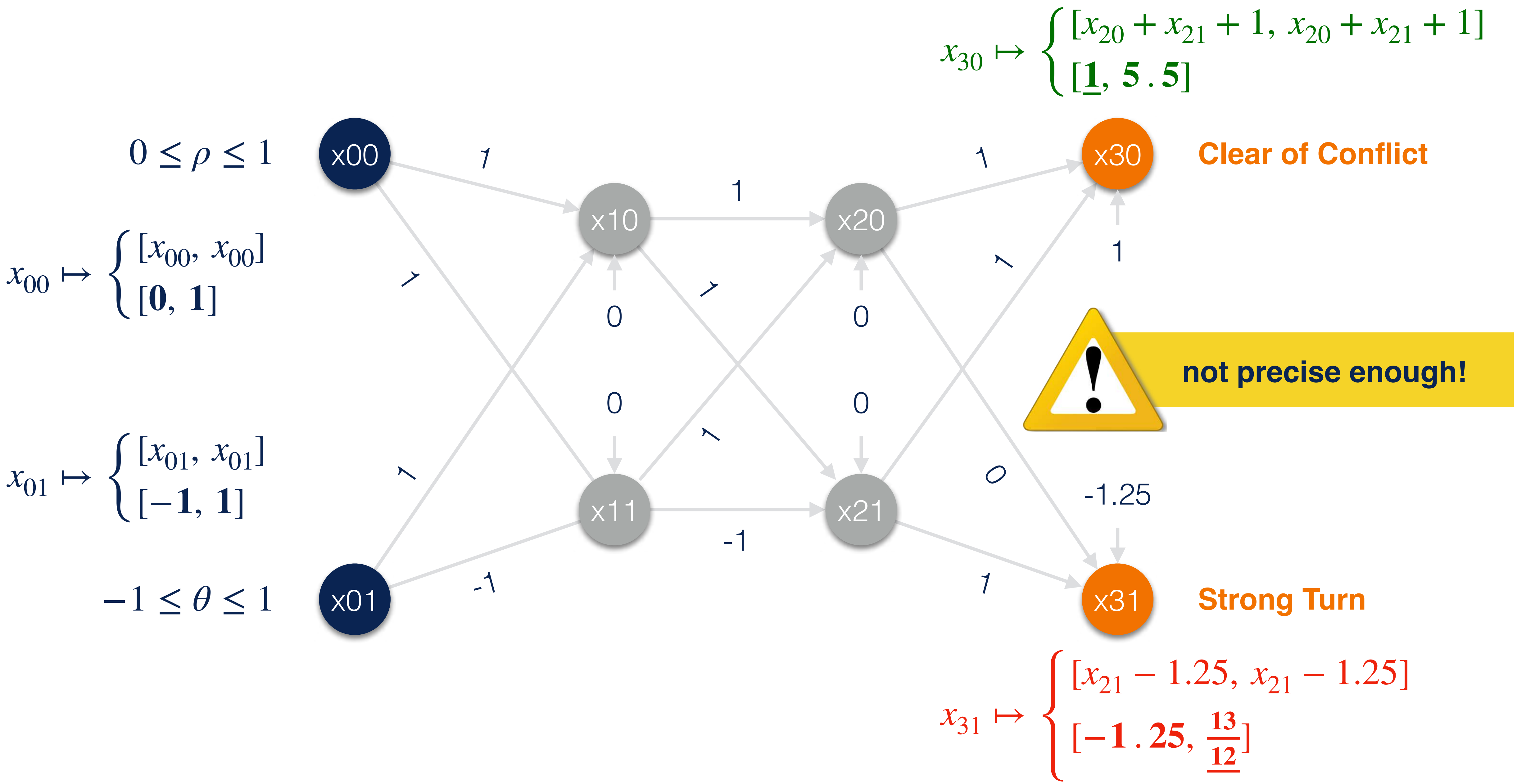
$$x_{21} \mapsto \begin{cases} [x_{10} - x_{11},\ x_{10} - x_{11}] \\ [-\frac{\mathbf{7}}{\mathbf{3}},\ \frac{\mathbf{7}}{\mathbf{3}}] \end{cases}$$

ReLU

$$x_{21} \mapsto \begin{cases} [0,\ 0.5 \cdot x_{21} + \frac{7}{6}] \\ [\mathbf{0},\ \frac{\mathbf{7}}{\mathbf{3}}] \end{cases}$$

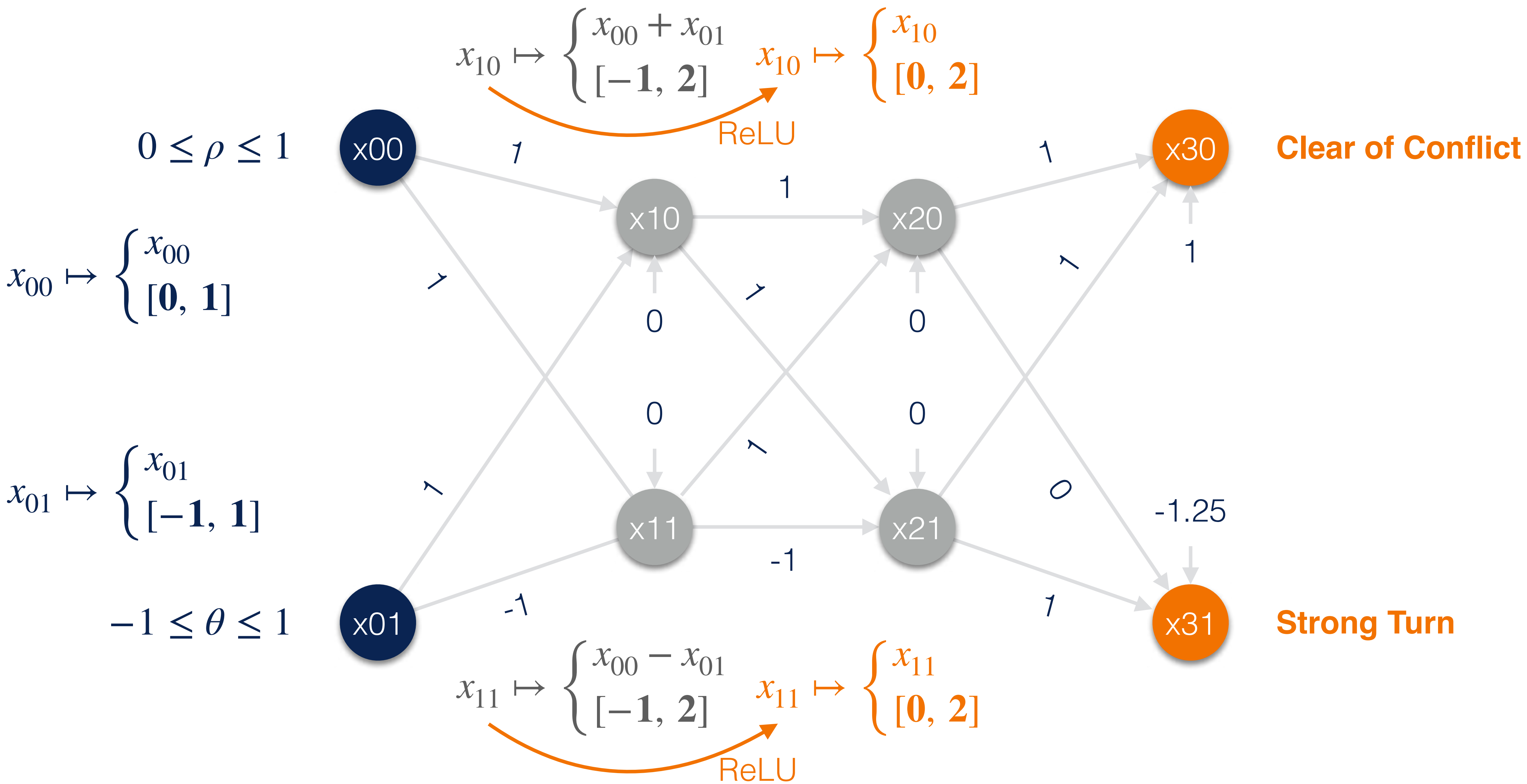


DeepPoly Domain [Singh19]



Interval Domain

with Symbolic Constant Propagation [Li19]



Interval Domain

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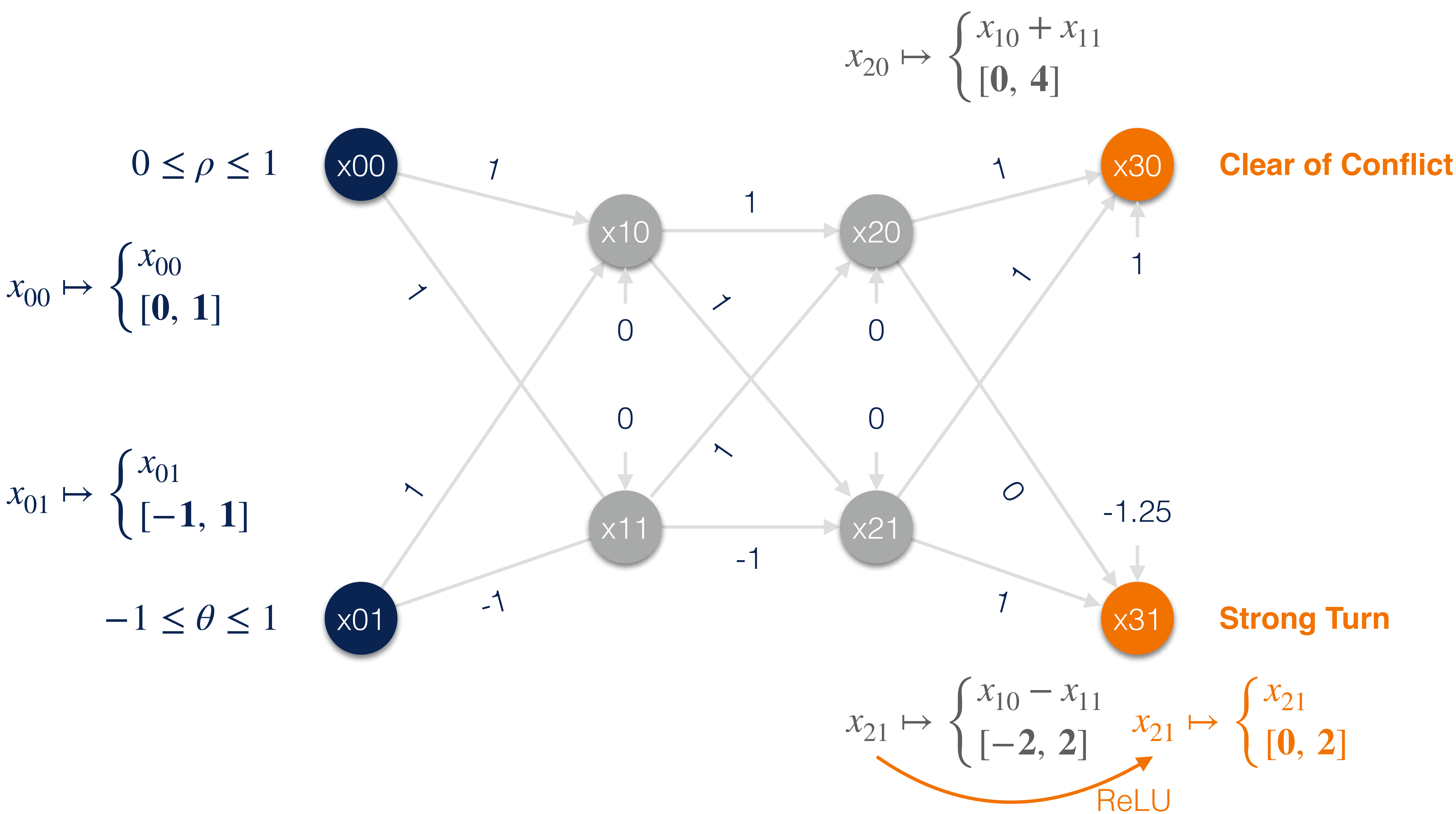
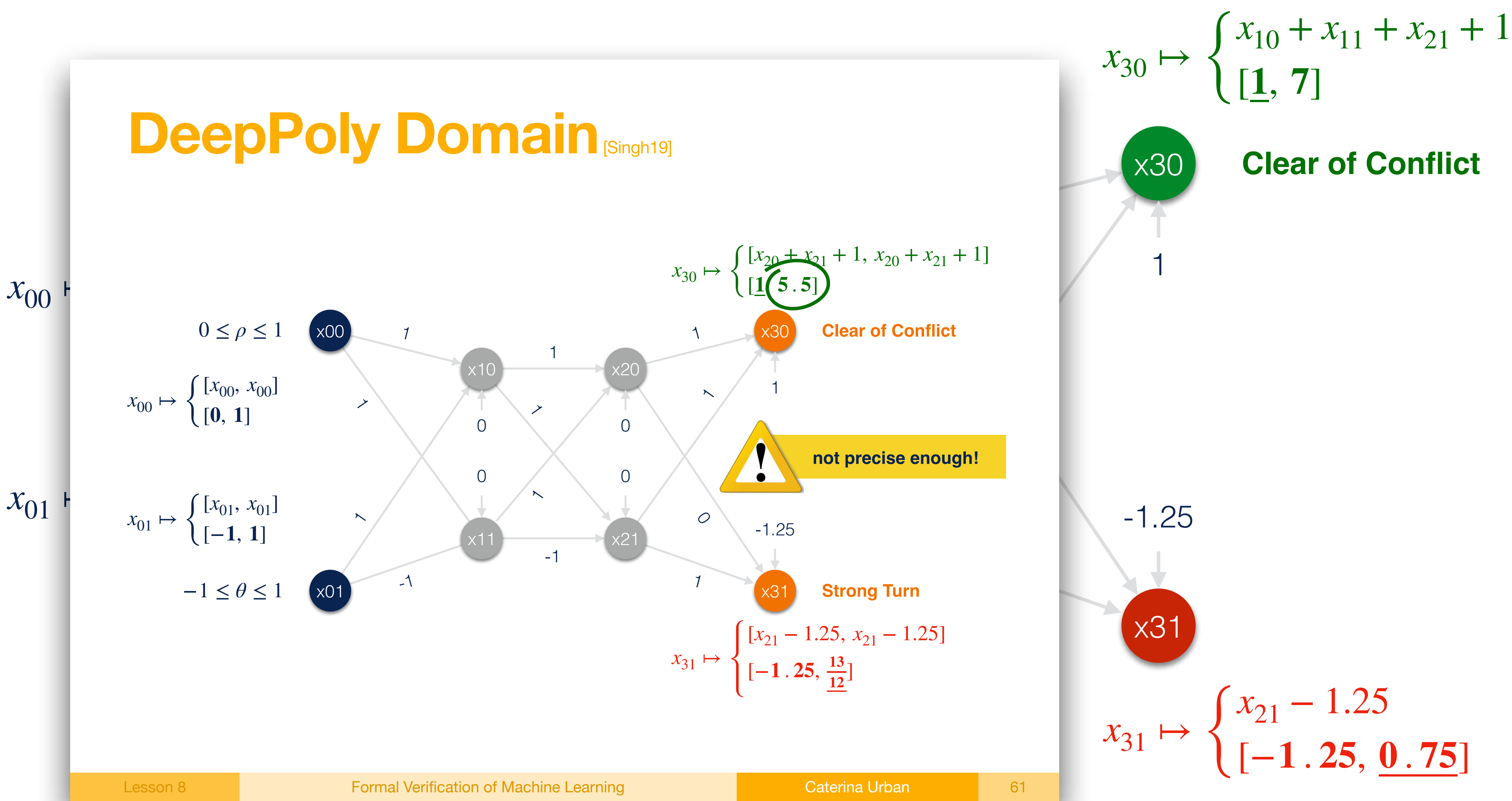
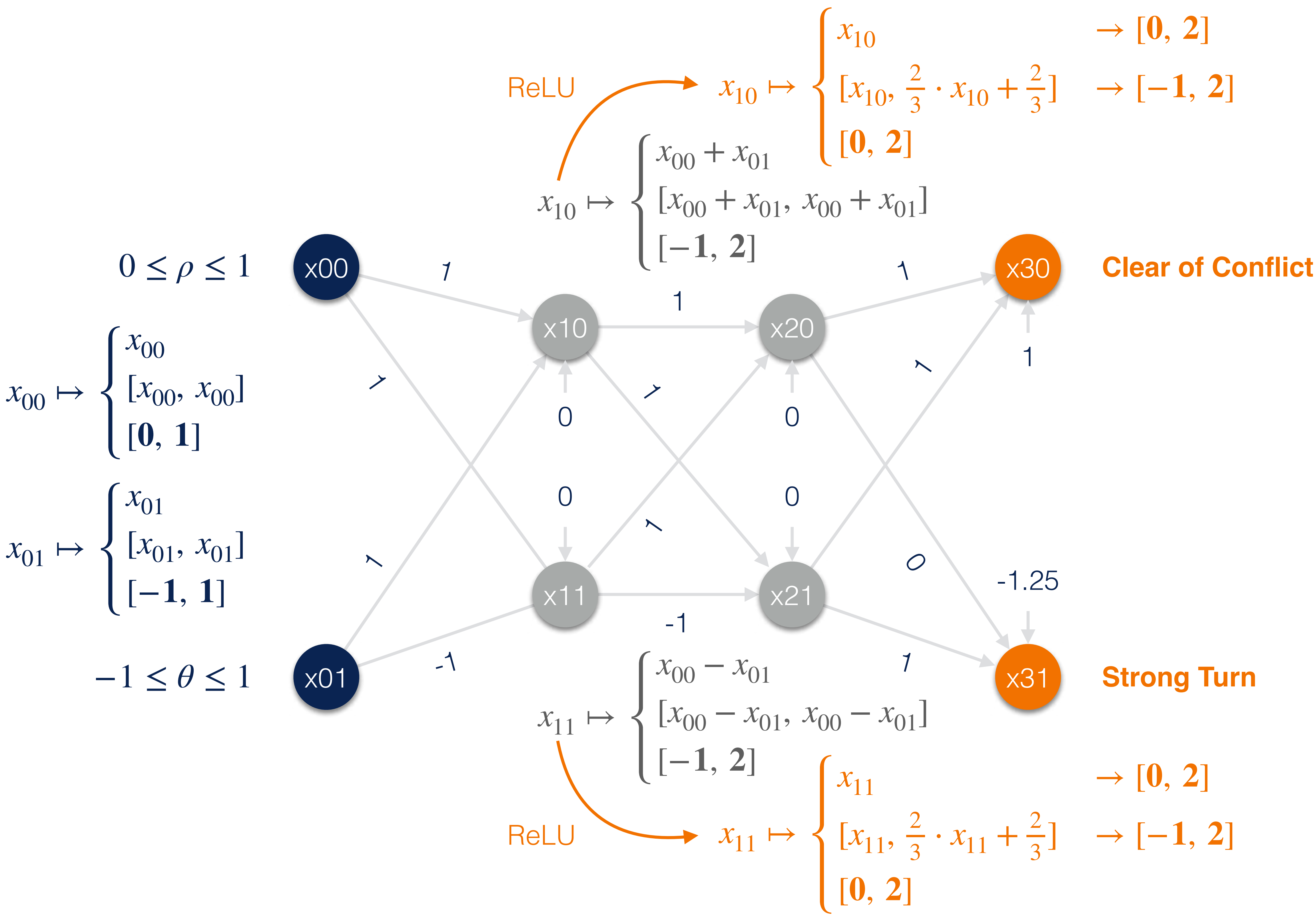


Interval Domain

with Symbolic Constant Propagation [Li19]



Product Domain [Mazzucato21]



Product Domain [Mazzucato21]

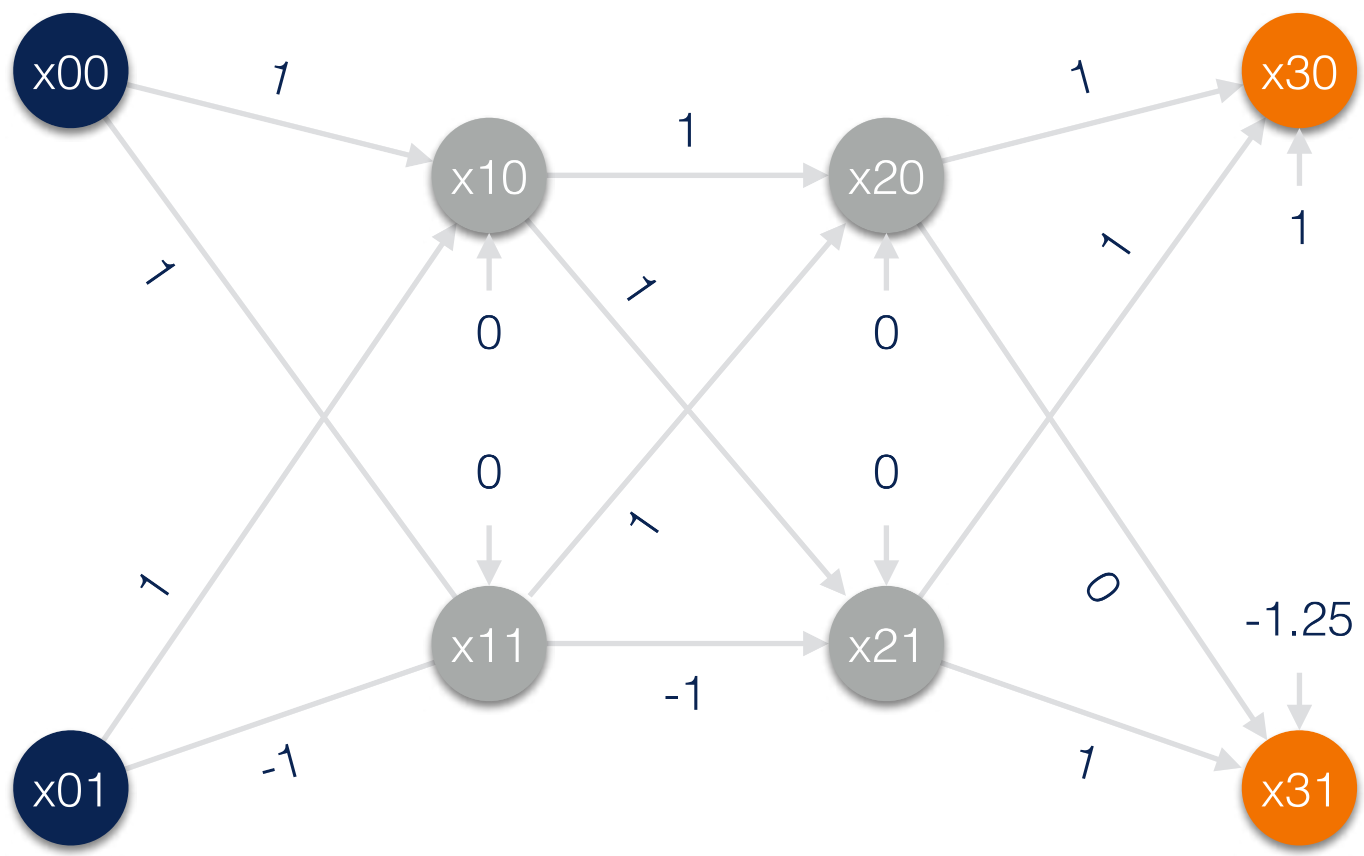
$$x_{20} \mapsto \begin{cases} x_{10} + x_{11} & \rightarrow [\mathbf{0},\ \mathbf{4}] \\ [x_{10} + x_{11},\ x_{10} + x_{11}] & \rightarrow [\mathbf{0},\ \frac{\mathbf{8}}{\mathbf{3}}] \\ [\mathbf{0},\ \frac{\mathbf{8}}{\mathbf{3}}] & \end{cases}$$

$0 \leq \rho \leq 1$

$$x_{00} \mapsto \begin{cases} x_{00} \\ [x_{00},\ x_{00}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

$$x_{01} \mapsto \begin{cases} x_{01} \\ [x_{01},\ x_{01}] \\ [\mathbf{-1},\ \mathbf{1}] \end{cases}$$

$-1 \leq \theta \leq 1$



Clear of Conflict

Strong Turn

$$x_{21} \mapsto \begin{cases} x_{10} - x_{11} & \rightarrow [\mathbf{-2},\ \mathbf{2}] \\ [x_{10} - x_{11},\ x_{10} - x_{11}] & \rightarrow [-\frac{\mathbf{7}}{\mathbf{3}},\ \frac{\mathbf{7}}{\mathbf{3}}] \\ [\mathbf{-2},\ \mathbf{2}] & \end{cases}$$

ReLU

$$x_{21} \mapsto \begin{cases} x_{21} & \rightarrow [\mathbf{0},\ \mathbf{2}] \\ [0,\ 0.5 \cdot x_{21} + 0.5] & \rightarrow [\mathbf{0},\ \frac{\mathbf{5}}{\mathbf{3}}] \\ [\mathbf{0},\ \frac{\mathbf{5}}{\mathbf{3}}] & \end{cases}$$

Product Domain [Mazzucato21]

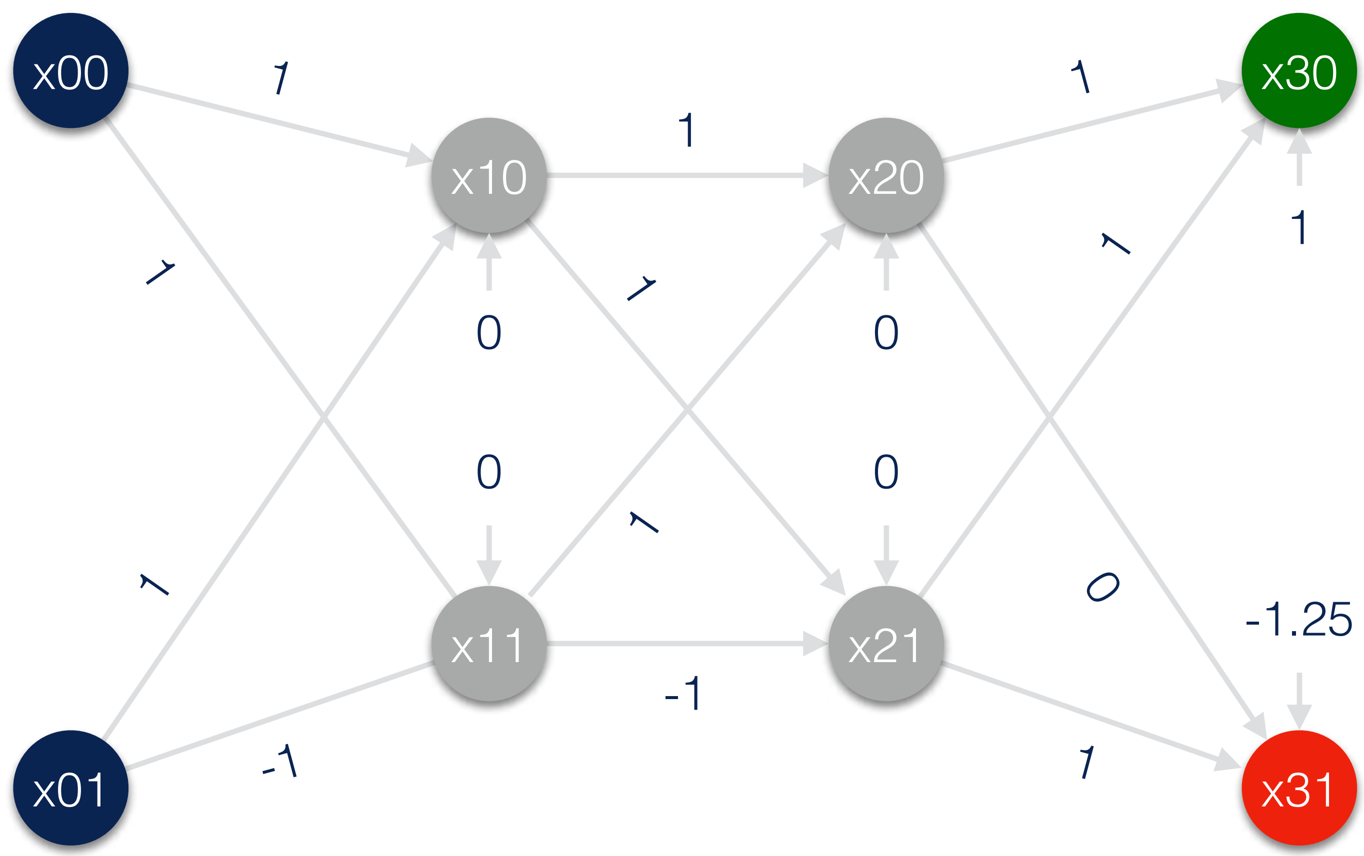
$$x_{30} \mapsto \begin{cases} x_{10} + x_{11} + x_{21} + 1 & \to [\mathbf{1},\ \tfrac{\mathbf{20}}{\mathbf{3}}] \\ [x_{20} + x_{21} + 1,\ x_{20} + x_{21} + 1] & \to [\mathbf{1},\ \mathbf{4.5}] \\ [\underline{\mathbf{1}},\ \mathbf{4.5}] \end{cases}$$

$0 \leq \rho \leq 1$

$$x_{00} \mapsto \begin{cases} x_{00} \\ [x_{00},\ x_{00}] \\ [\mathbf{0},\ \mathbf{1}] \end{cases}$$

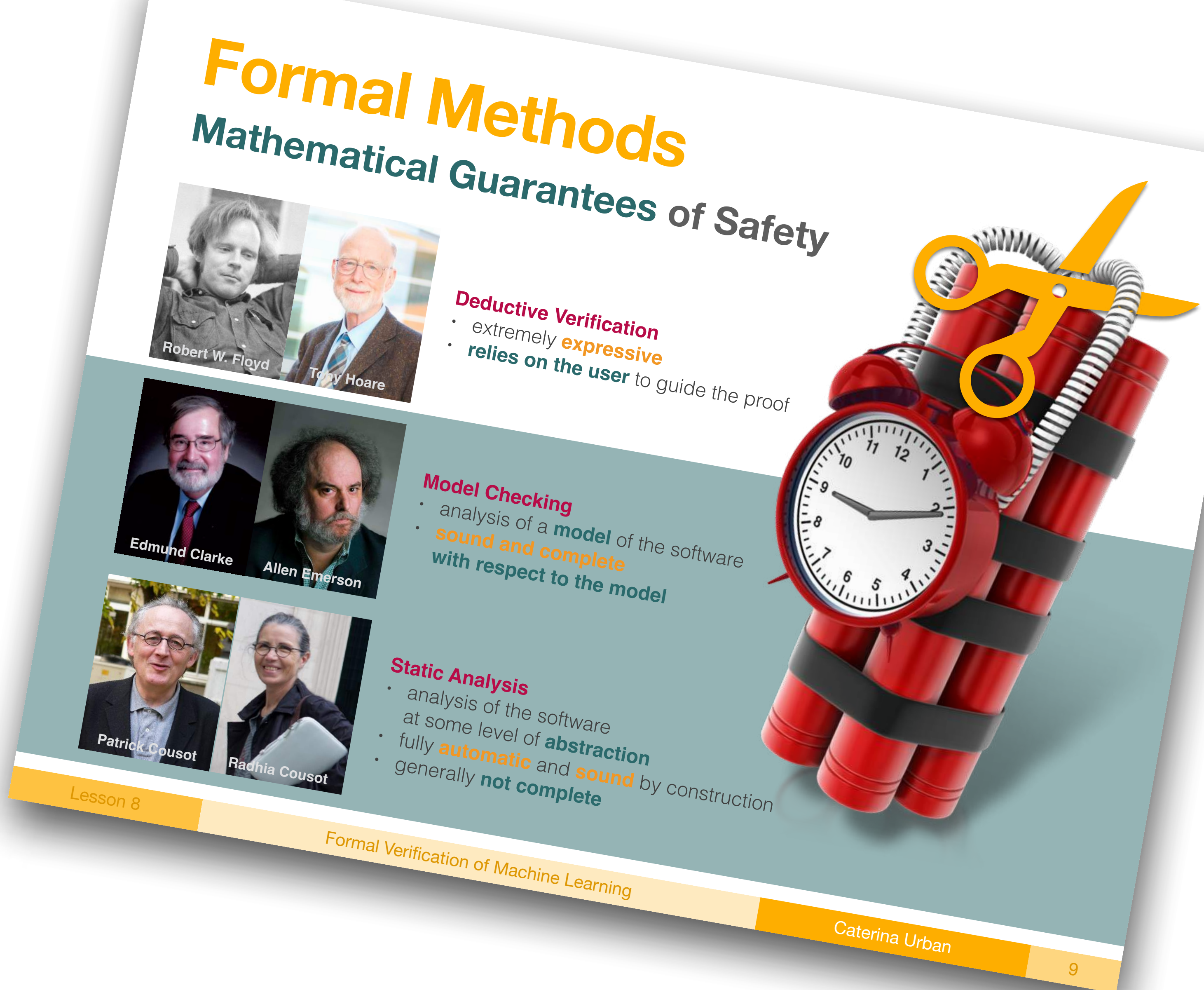
$$x_{01} \mapsto \begin{cases} x_{01} \\ [x_{01},\ x_{01}] \\ [\mathbf{-1},\ \mathbf{1}] \end{cases}$$

$-1 \leq \theta \leq 1$



Clear of Conflict

$$x_{31} \mapsto \begin{cases} x_{21} - 1.25 & \to [\mathbf{-1.25},\ \tfrac{\mathbf{5}}{\mathbf{12}}] \\ [x_{21} - 1.25,\ x_{21} - 1.25] & \to [\mathbf{-1.25},\ \tfrac{\mathbf{5}}{\mathbf{12}}] \\ [\mathbf{-1.25},\ \underline{\tfrac{\mathbf{5}}{\mathbf{12}}}] \end{cases}$$



Other Complete Methods

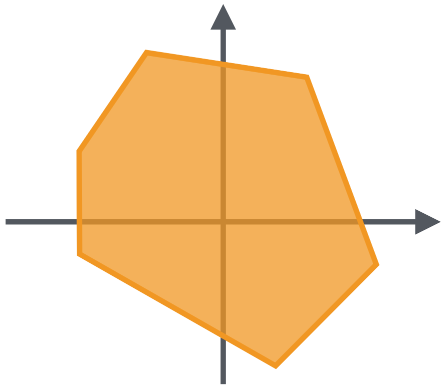
use **union** of
efficient representations
of **bounded convex polyhedra**

Star Sets

Exact Static Analysis Method

$\Theta \stackrel{\text{def}}{=} \langle c, V, P \rangle$

$c \in \mathcal{R}^n$: center
$V = \{v_1, \ldots, v_m\}$: basis vectors in $\mathcal{R}^n$
$P: \mathcal{R}^m \to \{ \bot, \top \}$: predicate



$[\![\Theta]\!] = \{x \mid x = c + \sum_{i=1}^{m} \alpha_i v_i \text{ such that } P(\alpha_1, \ldots, \alpha_m) = \top \}$

- fast and cheap **affine mapping operations** → neural network layers
- inexpensive **intersections with half-spaces** → ReLU activations

---

H.-D. Tran et al. - Star-Based Reachability Analysis of Deep Neural Networks (FM 2018)

Star Sets

Exact Static Analysis Method

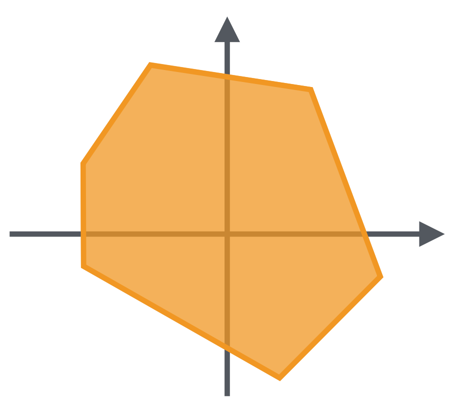
us
efficient
of bounded

Follow-up Work

H.-D. Tran et al. - Verification of Deep Convolutional Neural Networks Using ImageStars (CAV 2020)

$\Theta \stackrel{\text{def}}{=} \langle c, V, P \rangle$

$c \in \mathscr{R}^n$: center
$V = \{v_1, \ldots, v_m\}$: basis vectors in $\mathscr{R}^n$
$P : \mathscr{R}^m \rightarrow \{\perp, \top\}$: predicate



$$[\![\Theta]\!] = \{x \mid x = c + \sum_{i=1}^{m} \alpha_i v_i \text{ such that } P(\alpha_1, \ldots, \alpha_m) = \top \}$$

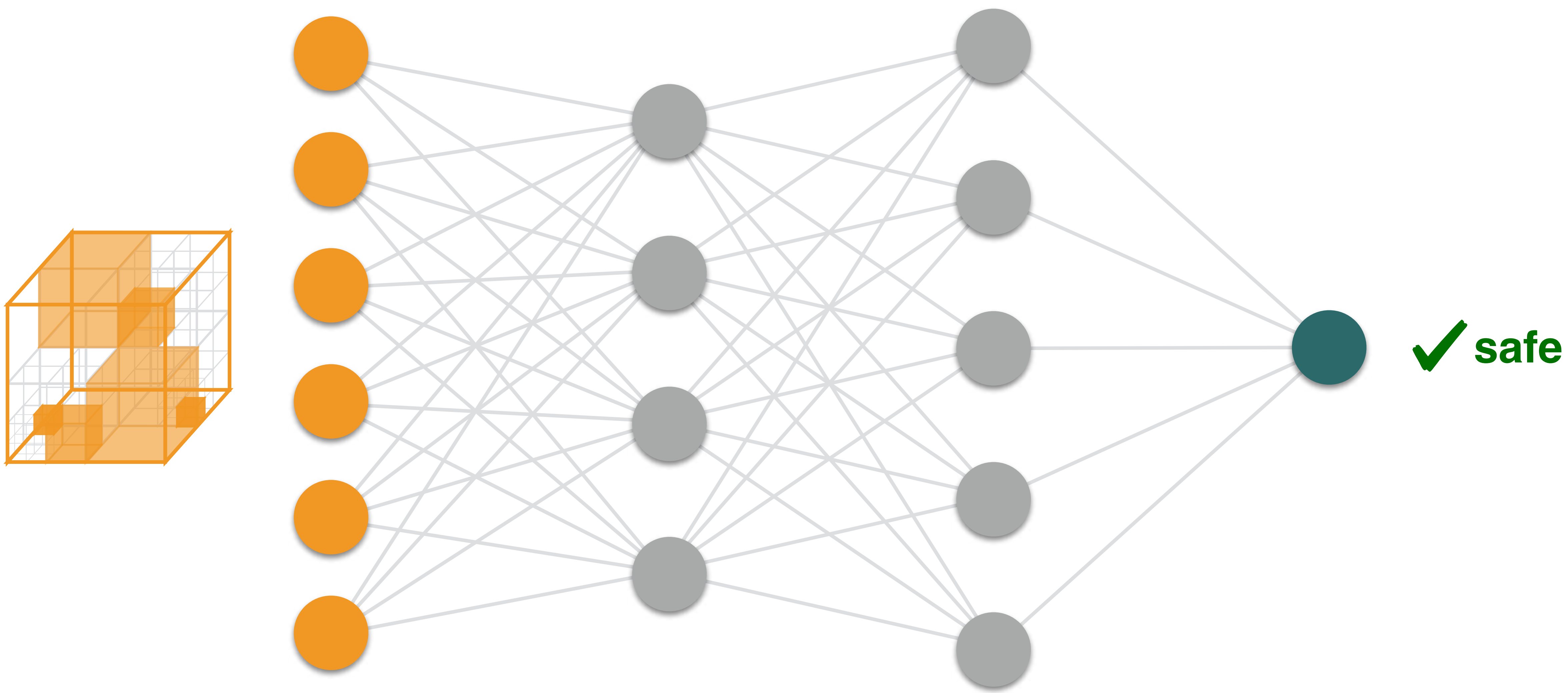
- fast and cheap **affine mapping operations** → neural network layers
- inexpensive **intersections with half-spaces** → ReLU activations

H.-D. Tran et al. - Star-Based Reachability Analysis of Deep Neural Networks (FM 2018)

ReluVal

use symbolic propagation
+ iterative input refinement

Asymptotically Complete Method



S. Wang et al. - Formal Security Analysis of Neural Networks Using Symbolic Intervals (USENIX Security 2018)

Neurify

Asymptotically Complete Method

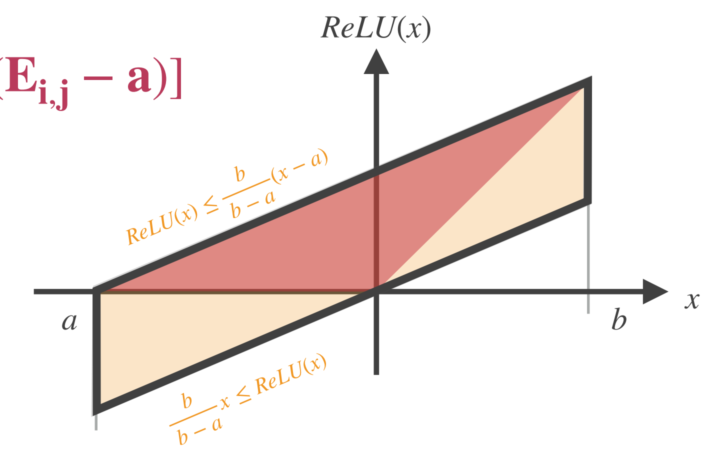
use symbolic propagation + convex ReLU approximation + iterative input/ReLU refinement

$$x_{i,j} \mapsto \begin{cases} [\sum_k c_{0,k} \cdot x_{0,k} + c,\ \sum_k d_{0,k} \cdot x_{0,k} + d] & c_{0,k}, c, d_{0,k}, d \in \mathscr{R} \\ [a,\ b] & a, b \in \mathscr{R} \end{cases}$$

$$x_{i,j} \mapsto \begin{cases} [\mathbf{E_{i,j}}, \mathbf{E_{i,j}}] \\ [\mathbf{a}, \mathbf{b}] \end{cases} \xrightarrow{\text{ReLU}} x_{i,j} \mapsto \begin{cases} [\mathbf{E_{i,j}}, \mathbf{E_{i,j}}] \\ [\mathbf{a}, \mathbf{b}] \end{cases} \qquad 0 \leq a$$

$$x_{i,j} \mapsto \begin{cases} [\mathbf{E_{i,j}}, \mathbf{E_{i,j}}] \\ [\mathbf{a}, \mathbf{b}] \end{cases} \xrightarrow{\text{ReLU}} x_{i,j} \mapsto \begin{cases} [\frac{\mathbf{b}}{\mathbf{b}-\mathbf{a}}\mathbf{E_{i,j}}, \frac{\mathbf{b}}{\mathbf{b}-\mathbf{a}}(\mathbf{E_{i,j}} - \mathbf{a})] \\ [\mathbf{a}, \mathbf{b}] \end{cases} \qquad a < 0 \wedge 0 < b$$

$$x_{i,j} \mapsto \begin{cases} [\mathbf{E_{i,j}}, \mathbf{E_{i,j}}] \\ [\mathbf{a}, \mathbf{b}] \end{cases} \xrightarrow{\text{ReLU}} x_{i,j} \mapsto \begin{cases} [\mathbf{0}, \mathbf{0}] \\ [\mathbf{0}, \mathbf{0}] \end{cases} \qquad b \leq 0$$

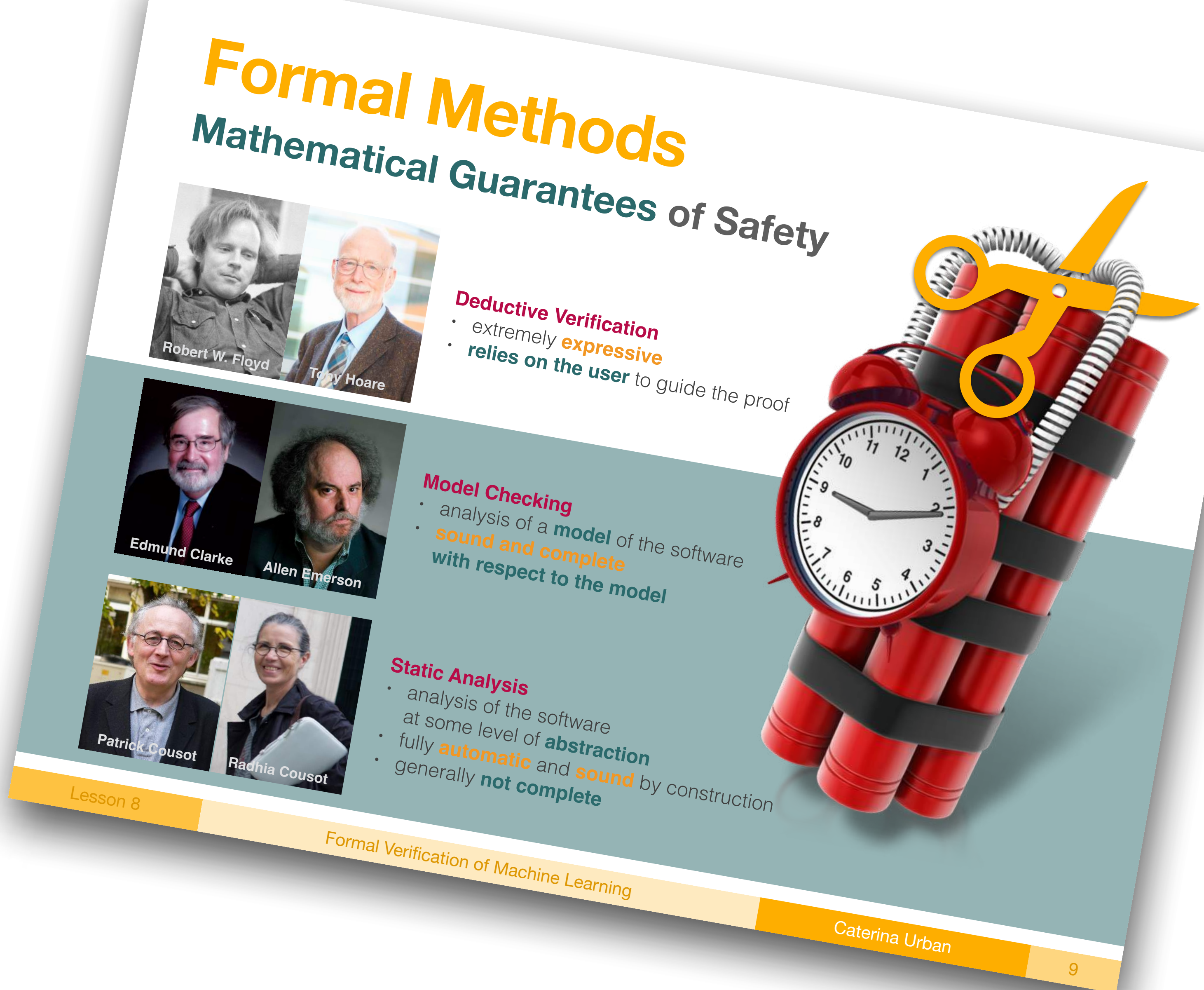


S. Wang et al. - Formal Security Analysis of Neural Networks Using Symbolic Intervals (USENIX Security 2018)

Further Complete Methods

- **W. Ruan, X. Huang, and M. Kwiatkowska**. *Reachability Analysis of Deep Neural Networks with Provable Guarantees*. In IJCAI, 2018.
  a global optimization-based approach for verifying Lipschitz continuous neural networks

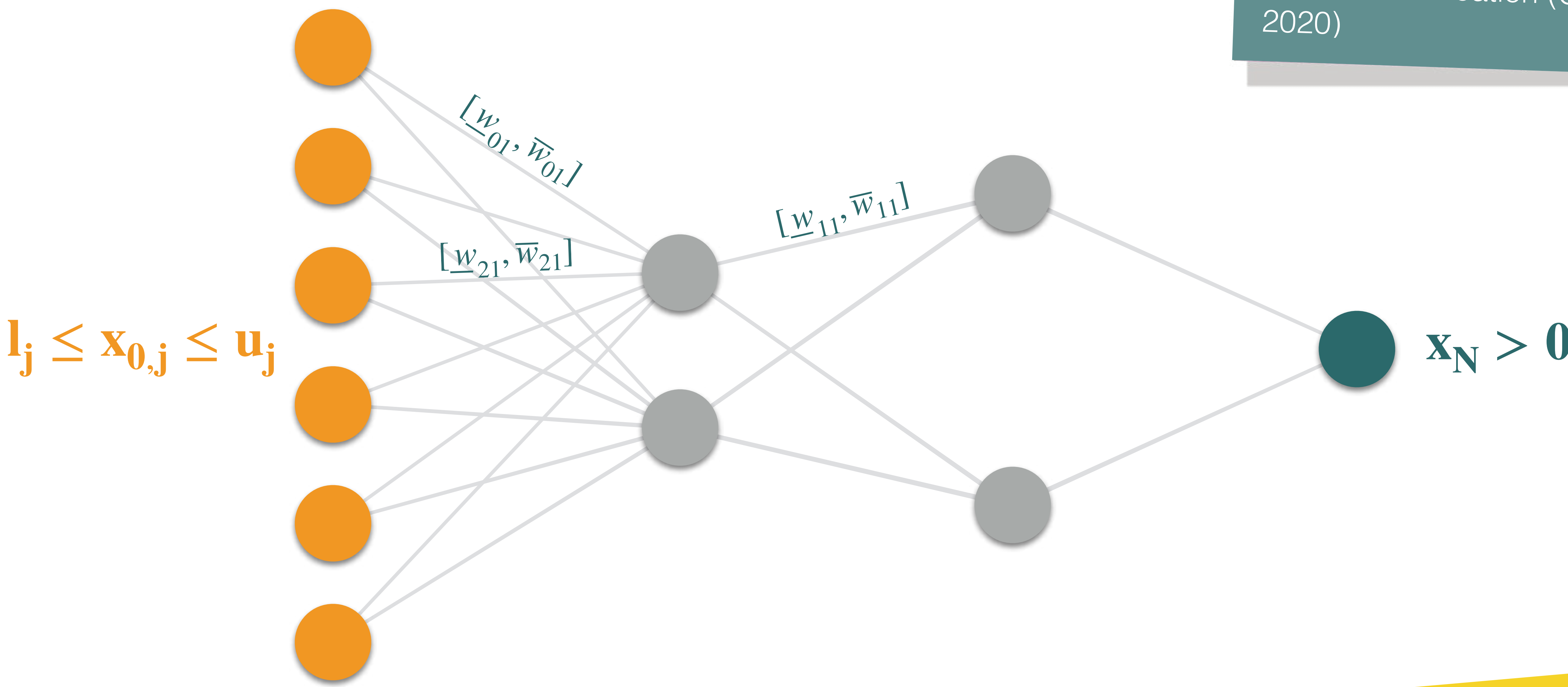
- **G. Singh, T. Gehr, M. Püschel, and M. Vechev**. *Boosting Robustness Certification of Neural Networks*. In ICLR, 2019.
  an approach combining abstract interpretation and (mixed integer) linear programming



Other Incomplete Methods

Interval Neural Networks

Abstraction-Based Method



Related Work

Y. Y. Elboher et al. - An Abstraction-Based Framework for Neural Network Verification (CAV 2020)

merge neurons layer-wise based on partitioning strategy + replace weights with intervals

P. Prabhakar and Z. R. Afza - Abstraction based Output Range Analysis for Neural Networks (NeurIPS 2019)

Further Incomplete Methods

- **W. Xiang, H.-D. Tran, and T. T. Johnson**. *Output Reachable Set Estimation and Verification for Multi-Layer Neural Networks*. 2018.
  an approach combining simulation and linear programming

- **K. Dvijotham, R. Stanforth, S. Gowal, T. Mann, and P. Kohli**. *A Dual Approach to Scalable Verification of Deep Networks*. In UAI, 2018.
  an approach based on duality for verifying neural networks

Further Incomplete Methods

- **E. Wong and Z. Kolter**. *Provable Defenses Against Adversarial Examples via the Convex Outer Adversarial Polytope*. In ICML, 2018.
  A. Raghunathan, J. Steinhardt, and P. Liang. *Certified Defenses against Adversarial Examples*. In ICML, 2018.
  T.-W. Weng, H. Zhang, H. Chen, Z. Song, C.-J. Hsieh, L. Daniel, D. Boning, and I. Dhillon. *Towards Fast Computation of Certified Robustness for ReLU Networks*. In ICML, 2018.
  H. Zhang, T.-W. Weng, P.-Y. Chen, C.-J. Hsieh, and L. Daniel. Efficient *Neural Network Robustness Certification with General Activation Functions*. In NeurIPS, 2018.
  approaches for finding a lower bound on robustness to adversarial perturbations

Further Incomplete Methods

- **A. Boopathy, T.-W. Weng, P.-Y. Chen, S. Liu, and L. Daniel**. *CNN-Cert: An Efficient Framework for Certifying Robustness of Convolutional Neural Networks*. In AAAI, 2019.
  approach focusing on convolutional neural networks

- **C.-Y. Ko, Z. Lyu, T.-W. Weng, L. Daniel, N. Wong, and D. Lin**. *POPQORN: Quantifying Robustness of Recurrent Neural Networks*. In ICML, 2019.
  H. Zhang, M. Shinn, A. Gupta, A. Gurfinkel, N. Le, and N. Narodytska. *Verification of Recurrent Neural Networks for Cognitive Tasks via Reachability Analysis*. In ECAI, 2020.
  approaches focusing on recurrent neural networks

- **D. Gopinath, H. Converse, C. S. Pasareanu, and A. Taly**. *Property Inference for Deep Neural Networks*. In ASE, 2019.
  an approach for inferring safety properties of neural networks

Complete Methods

Advantages

sound and complete

Disadvantages

soundness not typically guaranteed
with respect to floating-point arithmetic

do not scale to large models

often limited to certain
model architectures

Incomplete Methods

Advantages

less limited to certain
model architectures

sound often also with respect to
floating-point arithmetic

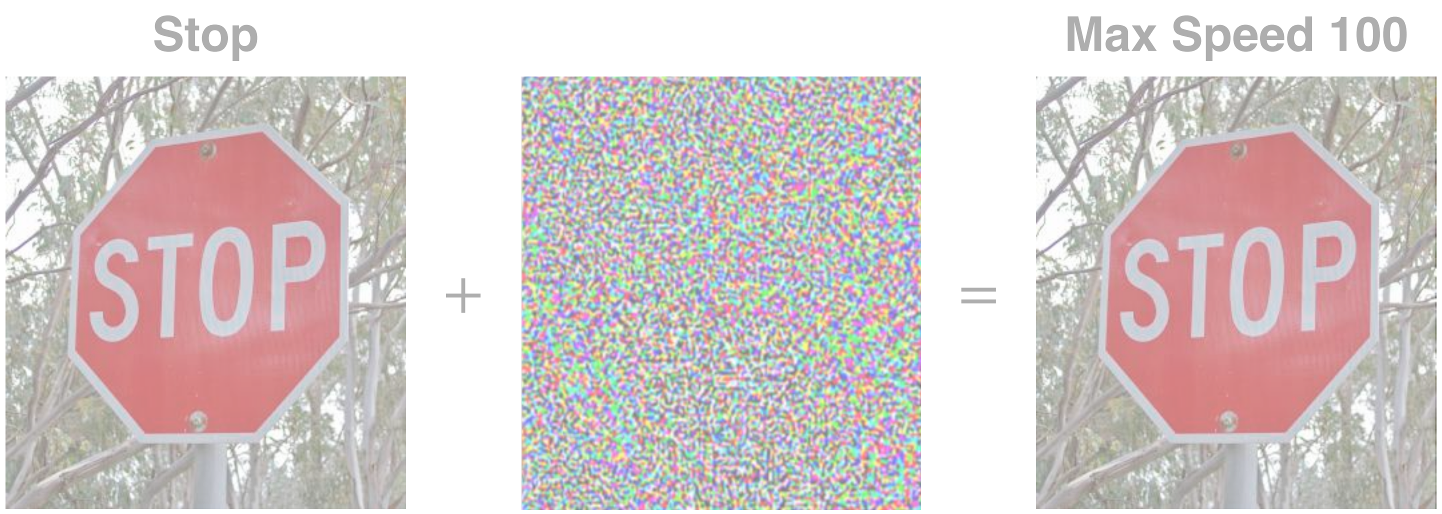
able to scale to large models

Disadvantages

suffer from false positives

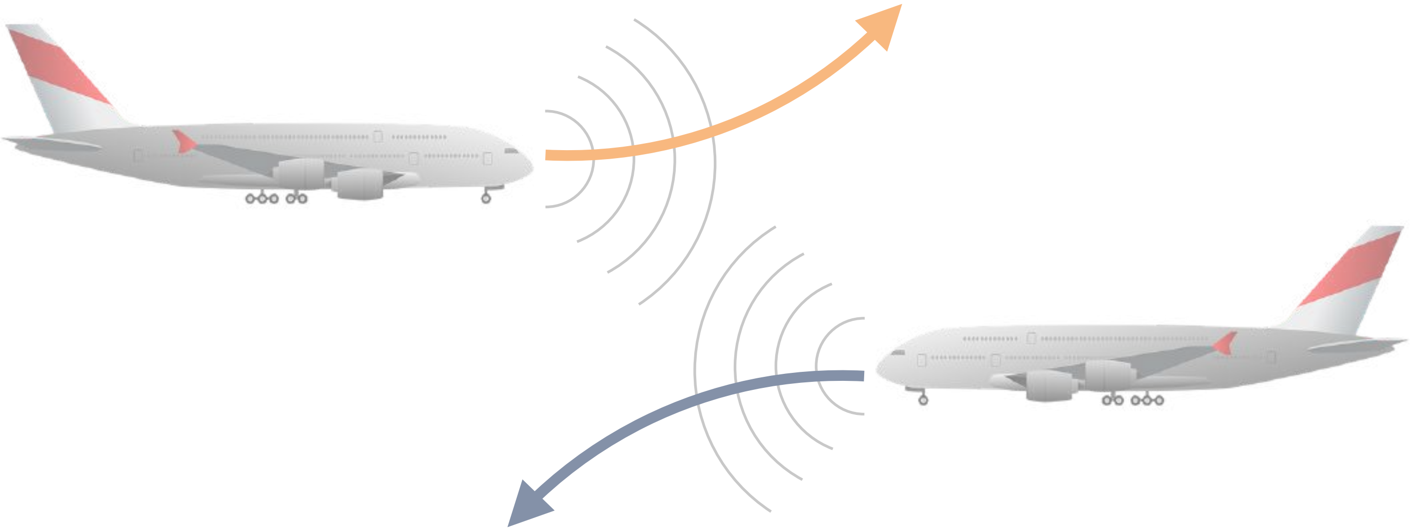
Stability

Goal G3 in [Kurd03]

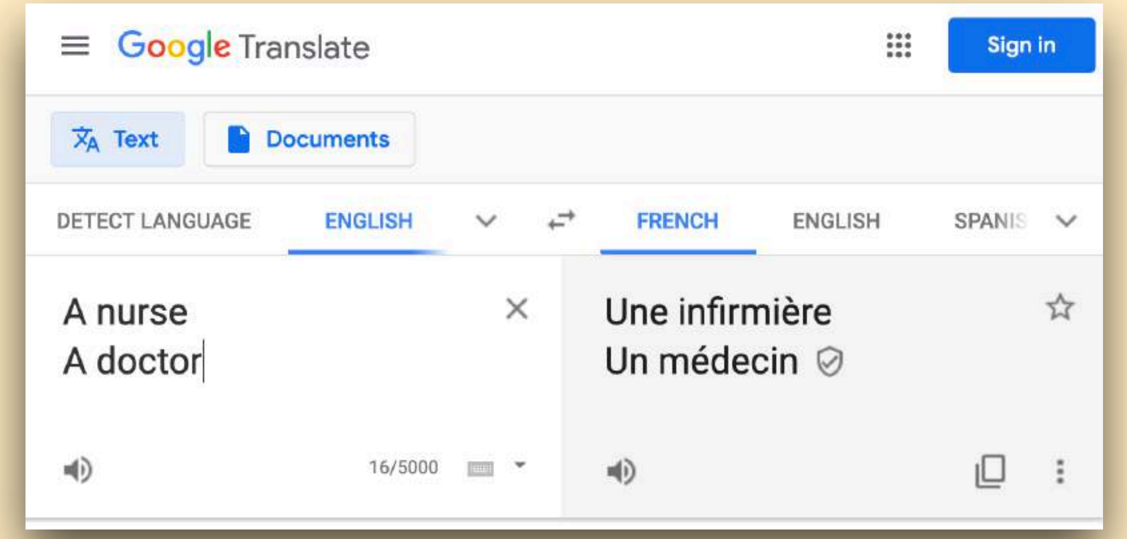


Safety

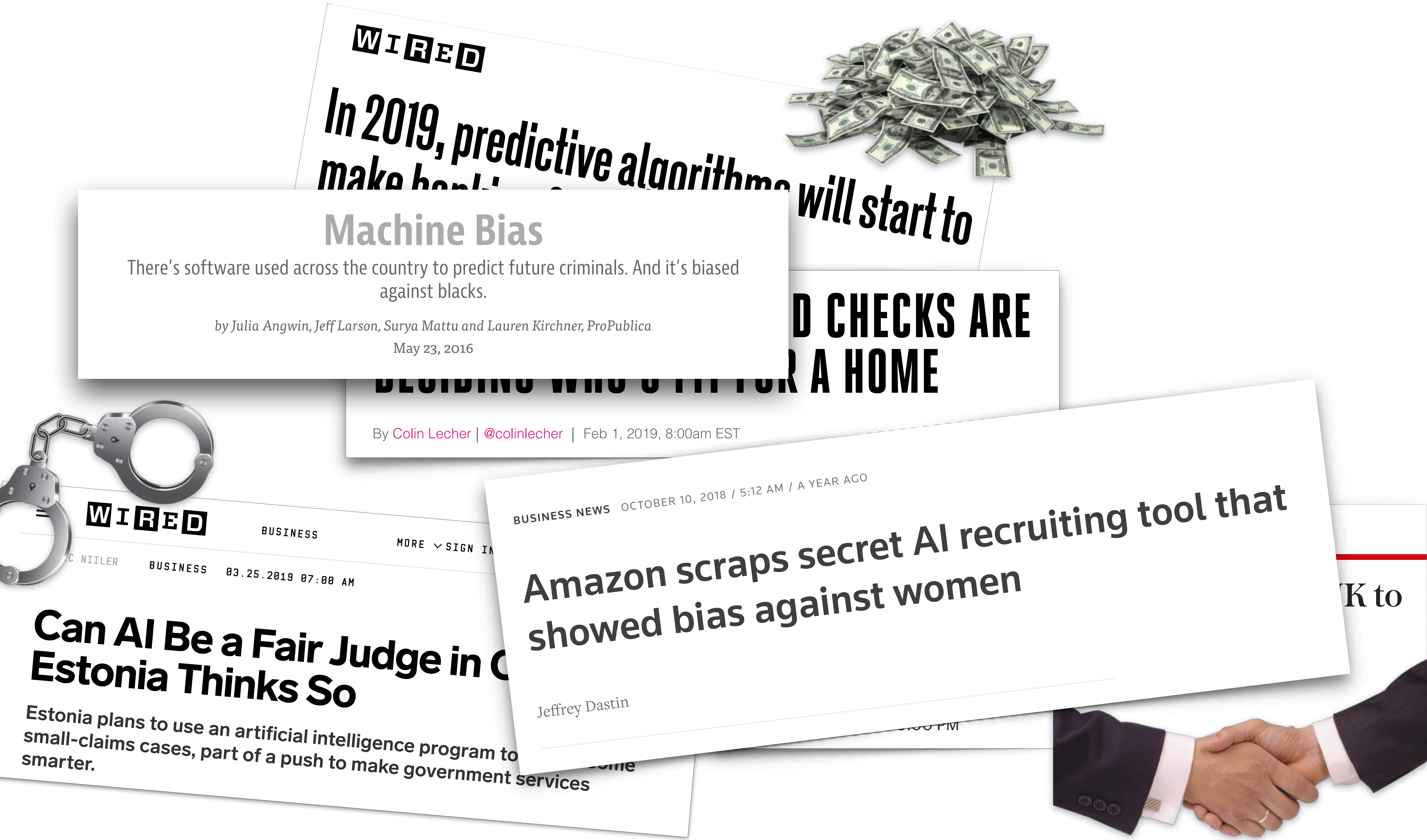
Goal G4 in [Kurd03]

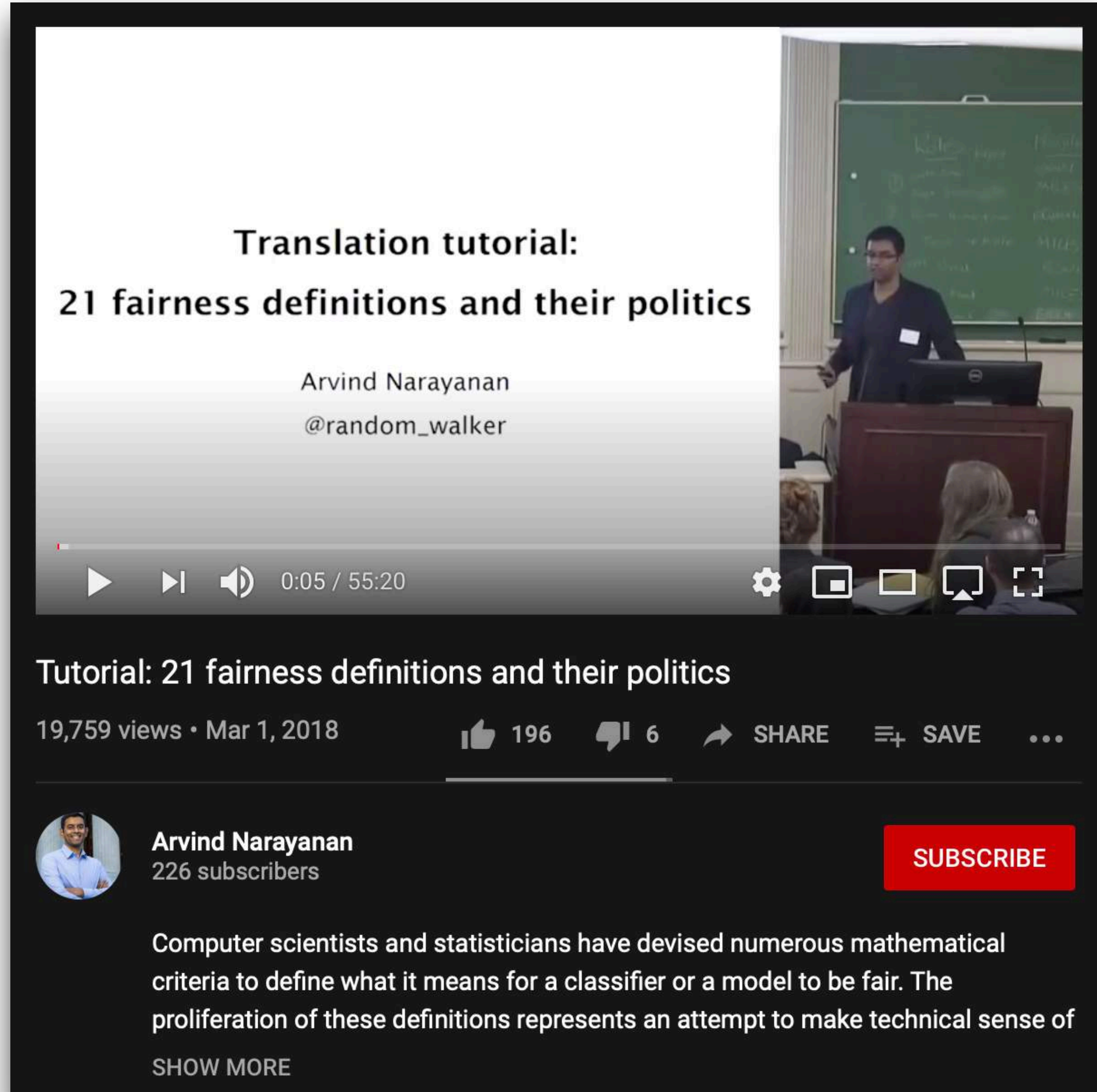


Fairness



ML Impacts Our Society




Translation tutorial:
21 fairness definitions and their politics
Arvind Narayanan
@random_walker
0:05 / 55:20
Tutorial: 21 fairness definitions and their politics
19,759 views • Mar 1, 2018
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6
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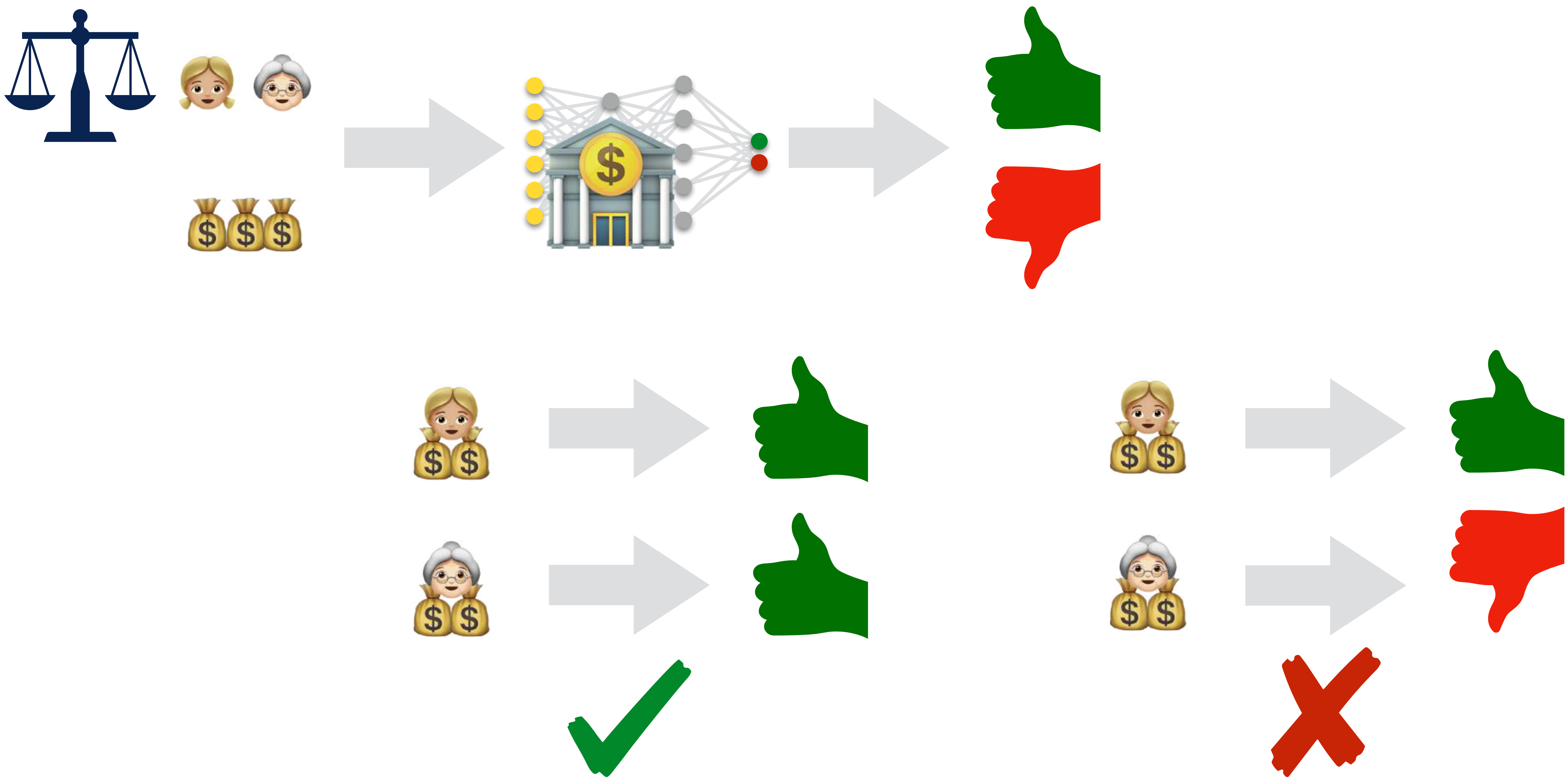
Computer scientists and statisticians have devised numerous mathematical criteria to define what it means for a classifier or a model to be fair. The proliferation of these definitions represents an attempt to make technical sense of
SHOW MORE

Dependency Fairness [Galhotra17]

The **classification** is **independent of** the values of the **sensitive inputs**



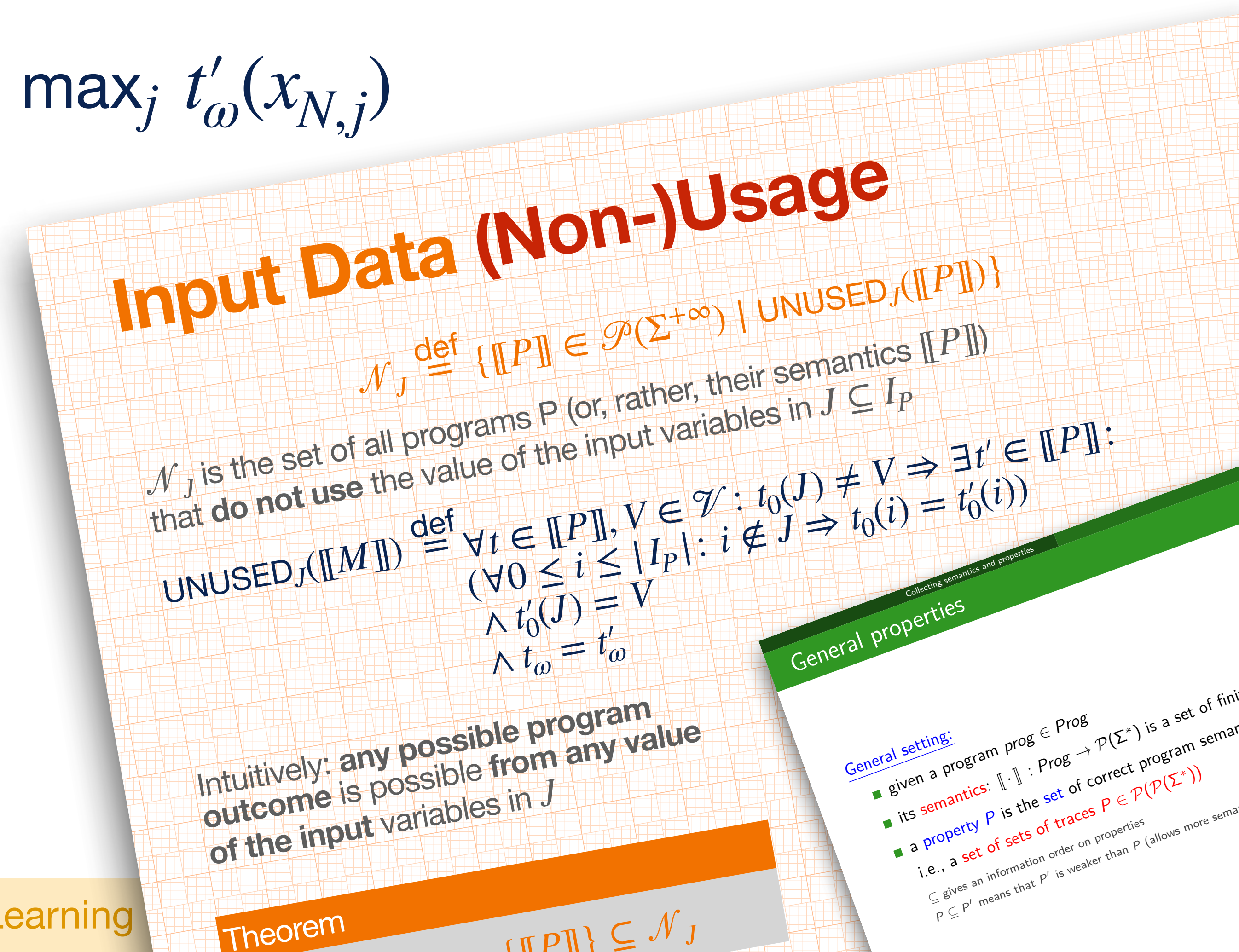
Dependency Fairness

$$\mathscr{F}_i \stackrel{\text{def}}{=} \{[\![M]\!] \in \mathscr{P}(\Sigma^*) \mid \text{UNUSED}_i([\![M]\!])\}$$

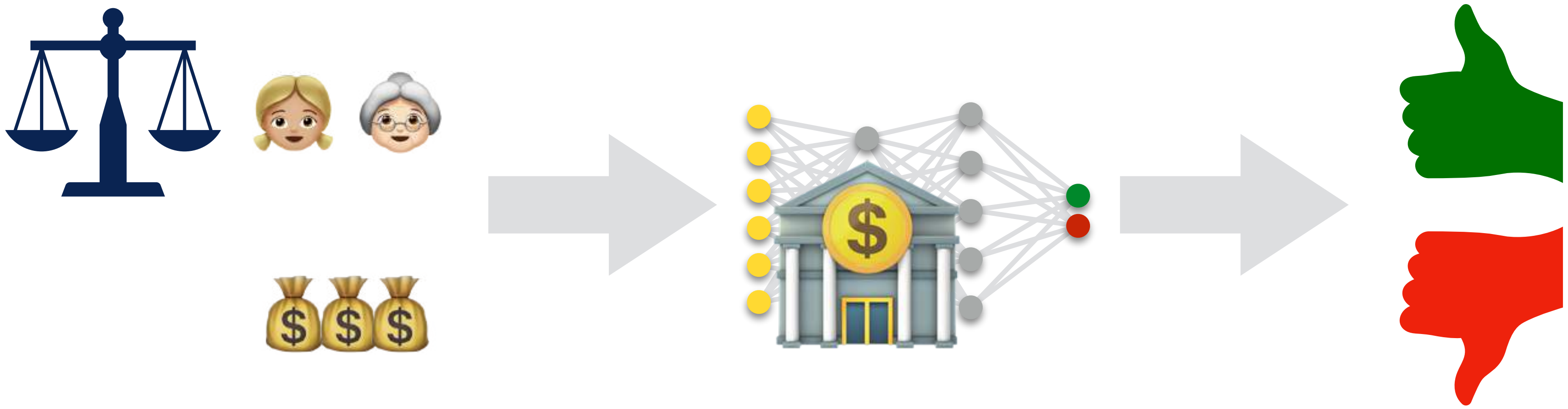
$\mathscr{F}_i$ is the set of all neural networks M (or, rather, their semantics $[\![M]\!]$) that **do not use** the value of the sensitive input node $x_{0,i}$ for classification

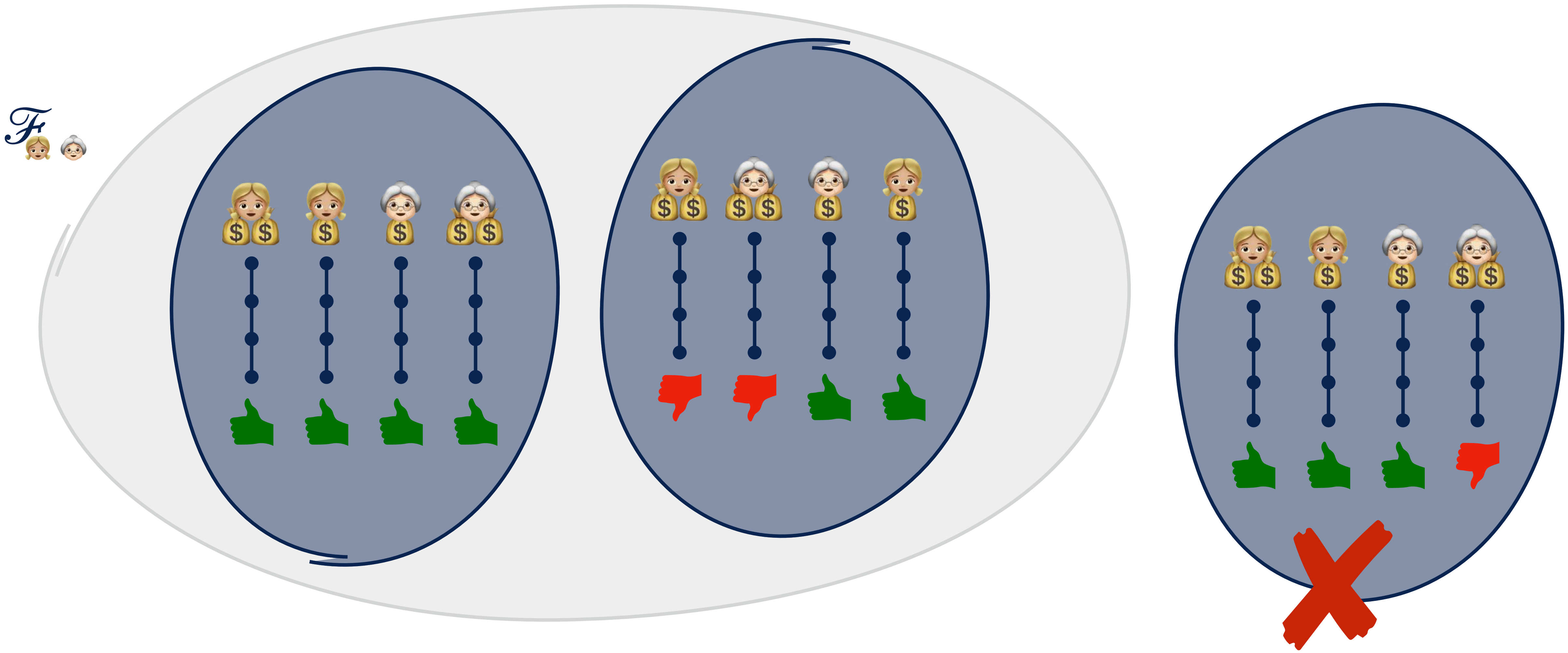
$$\begin{aligned}\text{UNUSED}_i([\![M]\!]) \stackrel{\text{def}}{=} \; & \forall t \in [\![M]\!], v \in \mathscr{R} \colon t_0(x_{0,i}) \neq v \Rightarrow \exists t' \in [\![M]\!] \colon \\ & (\forall 0 \leq j \leq |L_0| \colon j \neq i \Rightarrow t_0(x_{0,j}) = t'_0(x_{0,j})) \\ & \wedge t'_0(x_{0,i}) = v \\ & \wedge \max_j t_\omega(x_{N,j}) = \max_j t'_\omega(x_{N,j})\end{aligned}$$

Intuitively: **any possible classification outcome** is possible **from any value of the sensitive input** node $x_{0,i}$



Dependency Fairness





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Intuitively: **any possible classification outcome** is possible **from any value of the sensitive input** node $x_{0,i}$

Theorem

$$M \models \mathcal{F}_i \Leftrightarrow \{[\![M]\!]\} \subseteq \mathcal{F}_i$$

Hierarchy of Semantics

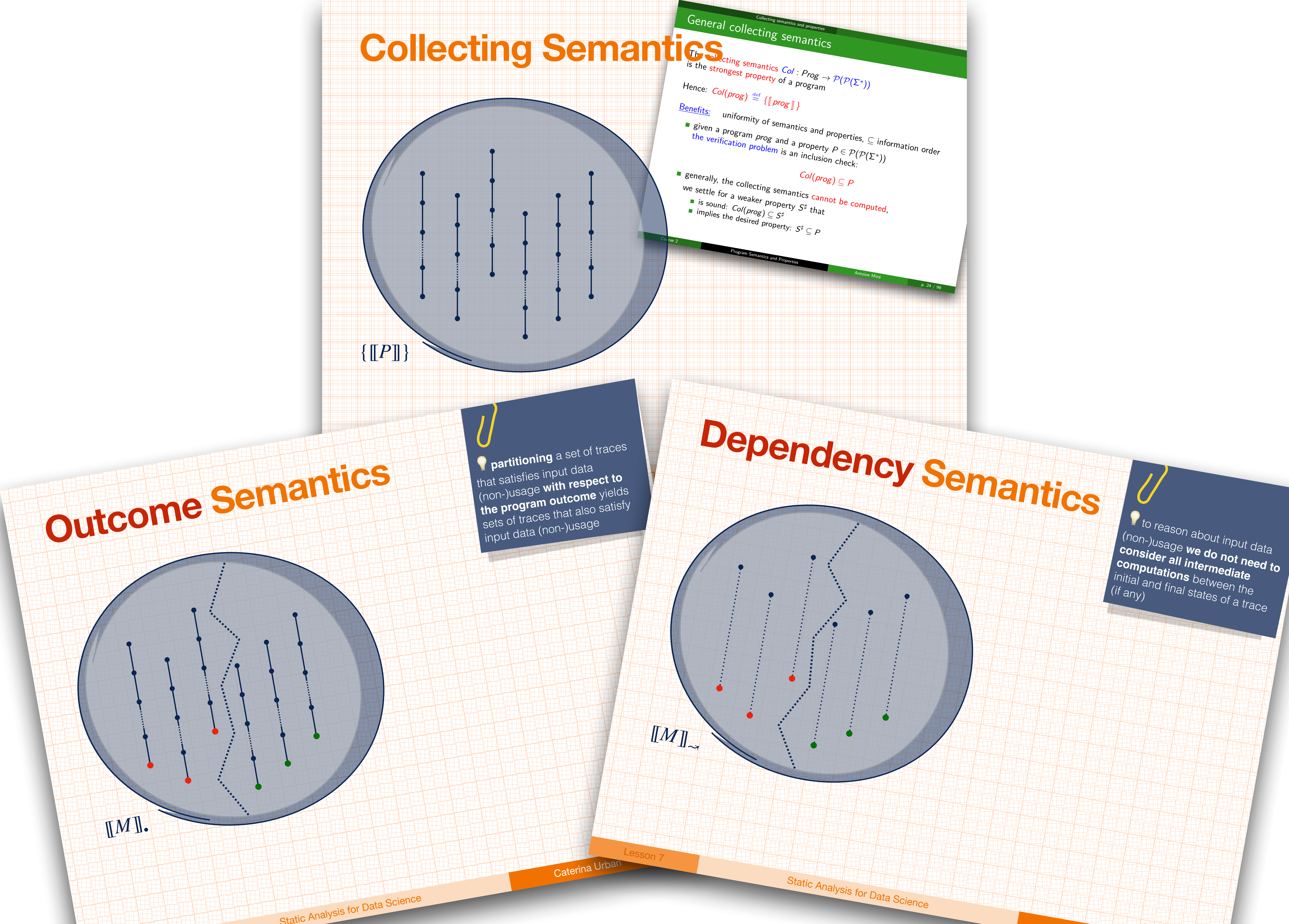
parallel semantics

dependency semantics

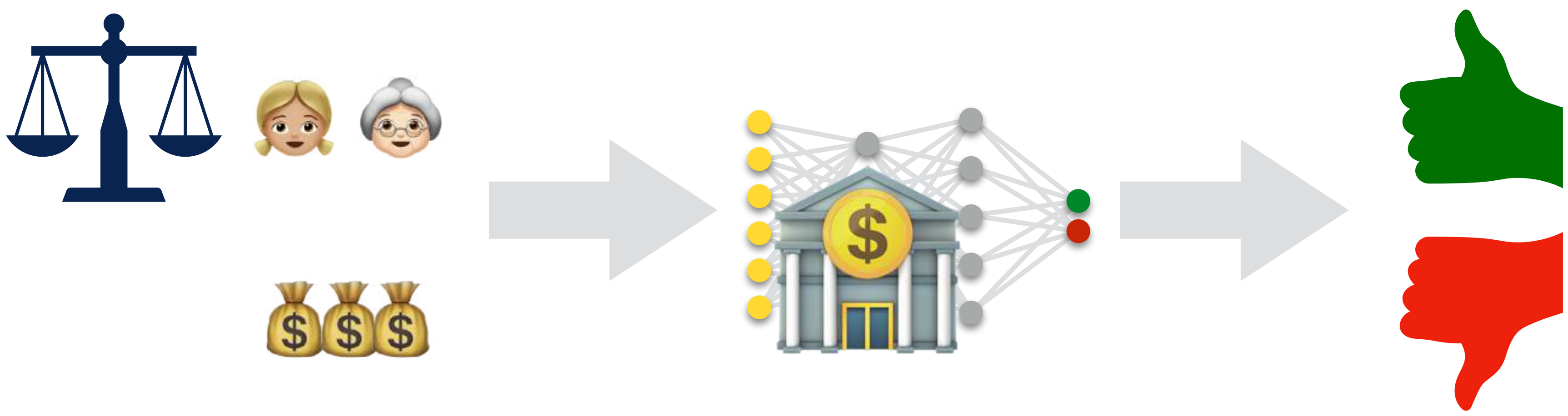
outcome semantics

collecting semantics

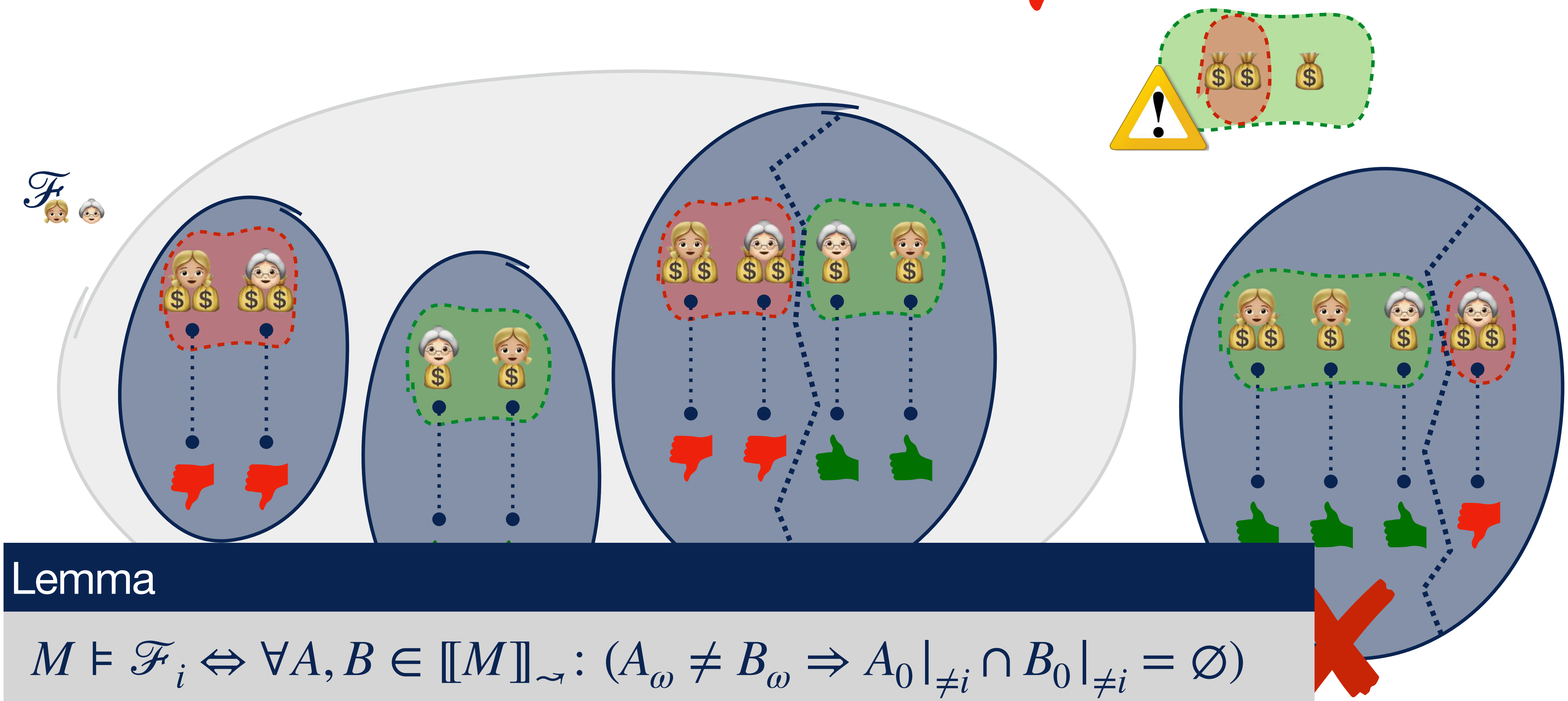
$$
\begin{tikzcd}
\{[M]\}^{\parallel}_{\rightsquigarrow} & \\
 & [\![M]\!]_{\rightsquigarrow} \arrow[ul, "\alpha_{\parallel}"'] \\
\{[M]\}^{\parallel}_{\bullet} \arrow[uu, "\alpha_{\rightsquigarrow}"] & \\
 & [\![M]\!]_{\bullet} \arrow[ul, "\alpha_{\parallel}"'] \arrow[uu, "\alpha_{\rightsquigarrow}"'] \\
\{[M]\}^{\parallel} \arrow[uu, "\alpha_{\bullet}"] & \\
 & \{[\![M]\!]\} \arrow[ul, "\alpha_{\parallel}"'] \arrow[uu, "\alpha_{\bullet}"']
\end{tikzcd}
$$


Collecting Semantics
{⟦P⟧}
Collecting semantics and properties
General collecting semantics
is the strongest property of a program
Hence: Col(prog) ≝ {⟦ prog ⟧}
Benefits: uniformity of semantics and properties, ⊆ information order
given a program prog and a property P ∈ 𝒫(𝒫(Σ*))
the verification problem is an inclusion check:
Col(prog) ⊆ P
generally, the collecting semantics cannot be computed,
we settle for a weaker property S♯ that
is sound: Col(prog) ⊆ S♯
implies the desired property: S♯ ⊆ P
Program Semantics and Properties
Antoine Miné
p. 24 / 98
Outcome Semantics
partitioning a set of traces that satisfies input data (non-)usage with respect to the program outcome yields sets of traces that also satisfy input data (non-)usage
⟦M⟧.
Lesson 7
Static Analysis for Data Science
Caterina Urban
Dependency Semantics
to reason about input data (non-)usage we do not need to consider all intermediate computations between the initial and final states of a trace (if any)
⟦M⟧⇝
Lesson 7
Static Analysis for Data Science
Caterina Urban
31

Dependency Semantics



💡 **partitioning with respect to the outcome** classification **induces a partition of the** space of **values** of the input nodes ***used* for classification**



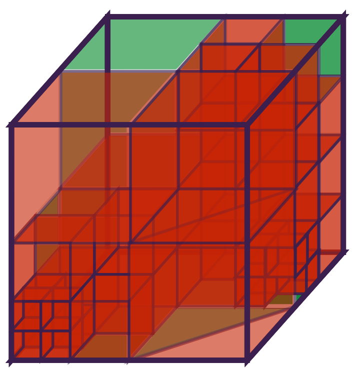
Lemma

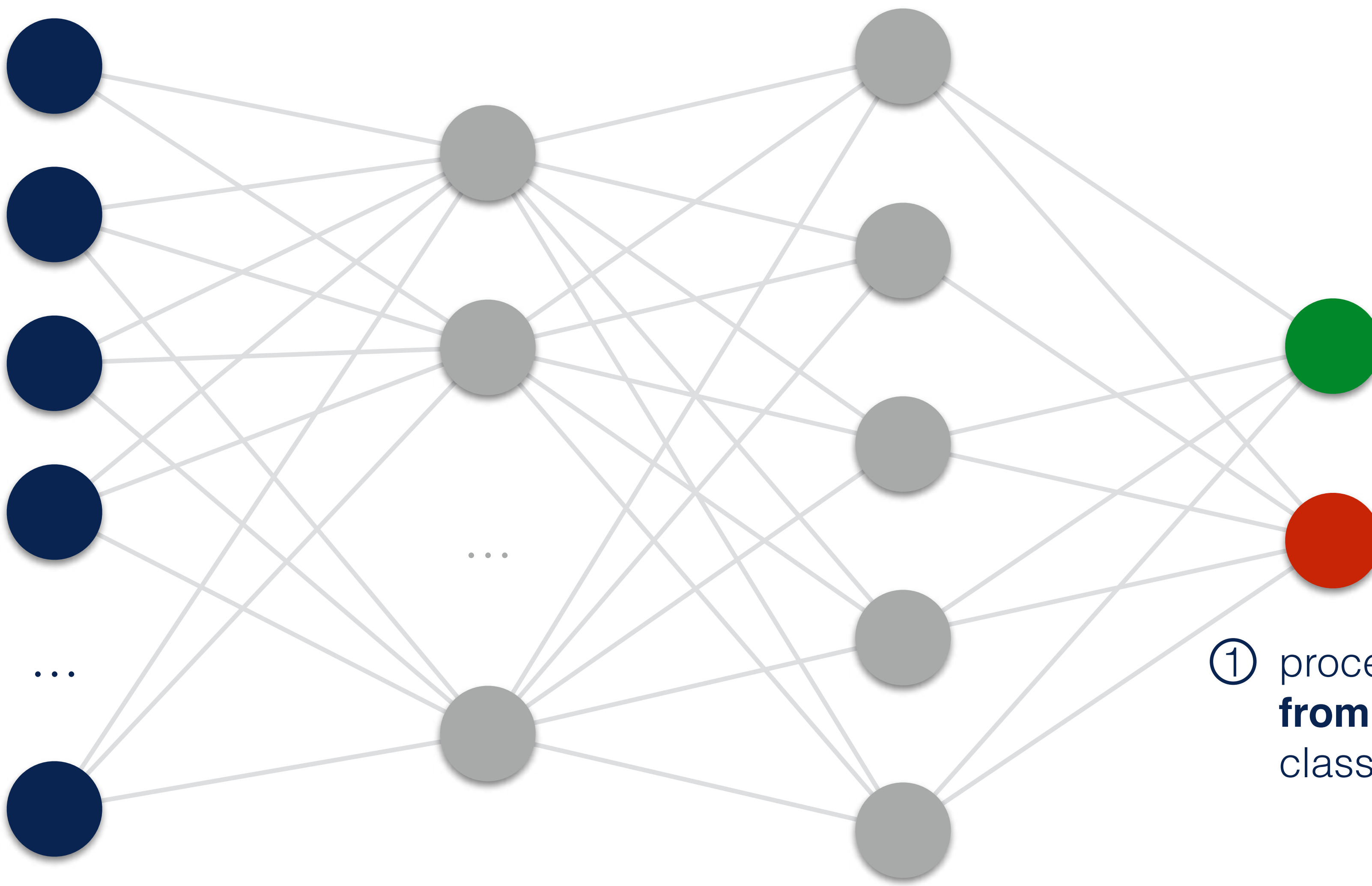
$$M \models \mathcal{F}_i \Leftrightarrow \forall A, B \in [\![M]\!]_{\rightsquigarrow} : (A_\omega \neq B_\omega \Rightarrow A_0|_{\neq i} \cap B_0|_{\neq i} = \emptyset)$$

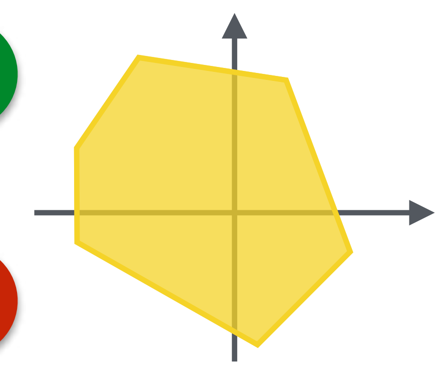
Naïve Abstraction

Naïve Backward Analysis

② **forget** the values of the **sensitive input** nodes



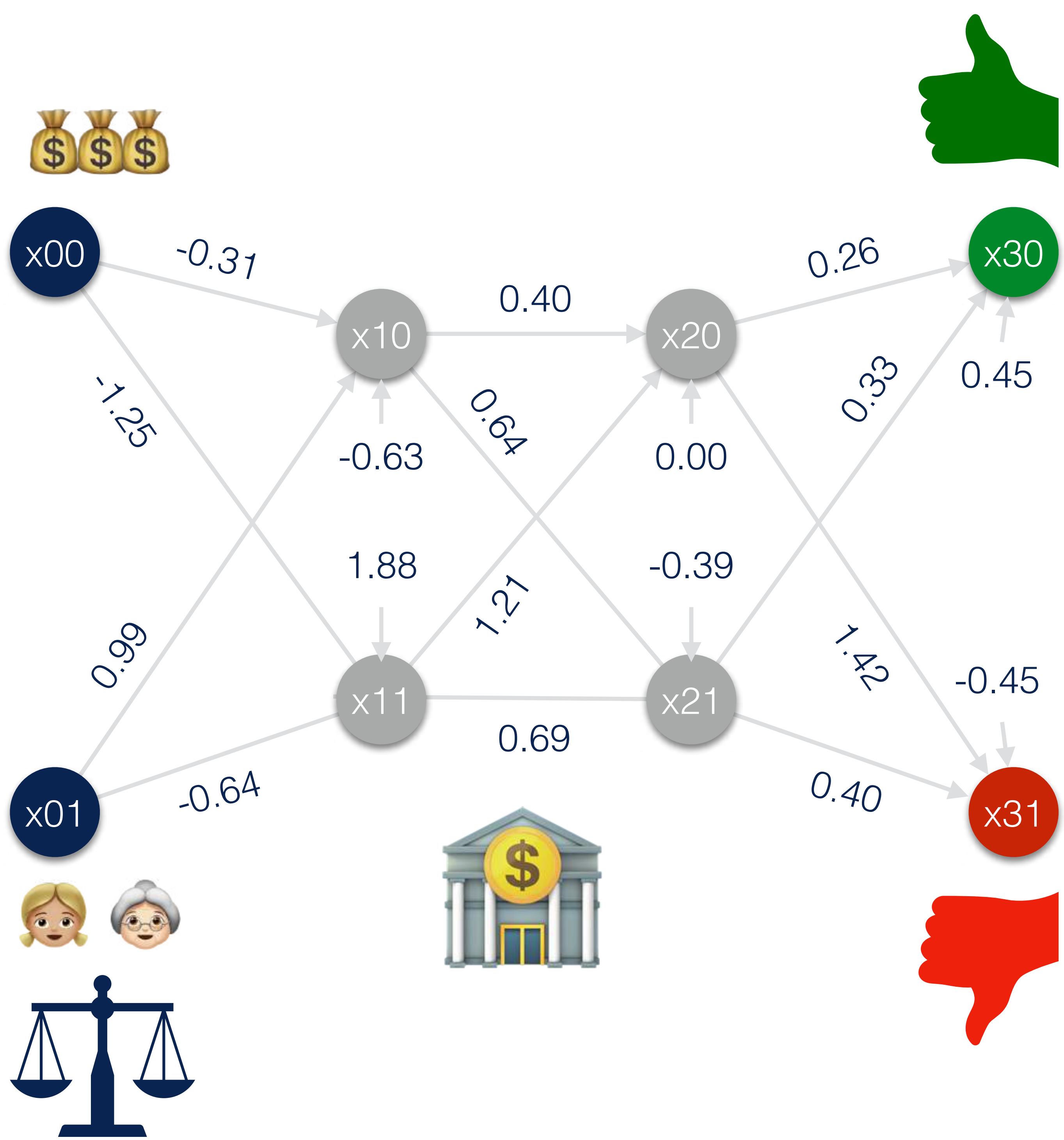




① proceed **backwards** **from all** possible classification **outcomes**

③ check for **intersection**:
empty → ✔ **fair**
otherwise → 🚨 **alarm**

Naïve Backward Analysis

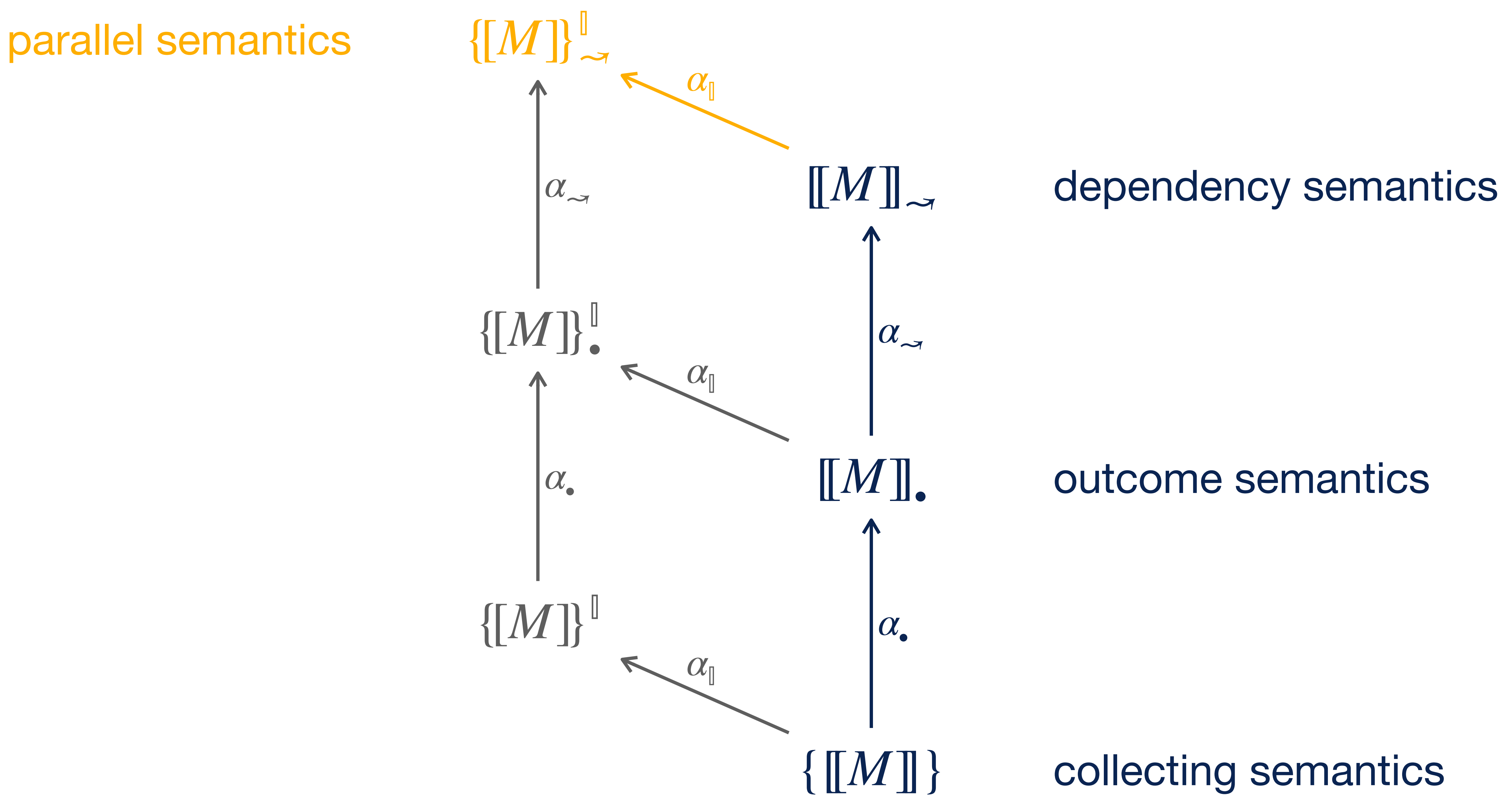



```
x00 = input()
x01 = input()
x10 = -0.31 * x00 + 0.99 * x01 + (-0.63)
x11 = -1.25 * x00 + (-0.64) * x01 + 1.88
x10 = 0 if x10 < 0 else x10
x11 = 0 if x11 < 0 else x11
x20 = 0.40 * x10 + 1.21 * x11 + 0.00
x21 = 0.64 * x10 + 0.69 * x11 + (-0.39)
x20 = 0 if x20 < 0 else x20
x21 = 0 if x21 < 0 else x21
1.16 * x20 + 0.07 * x21 ≤ 0.90      1.16 * x20 + 0.07 * x21 ≥ 0.90
x30 = 0.26 * x20 + 0.33 * x21 + 0.45
X31 = 1.42 * x20 + 0.40 * x21 + (-0.45)
x30 ≥ x31      x31 ≥ x30
return ' ' if x31 < 30 else ' '
```

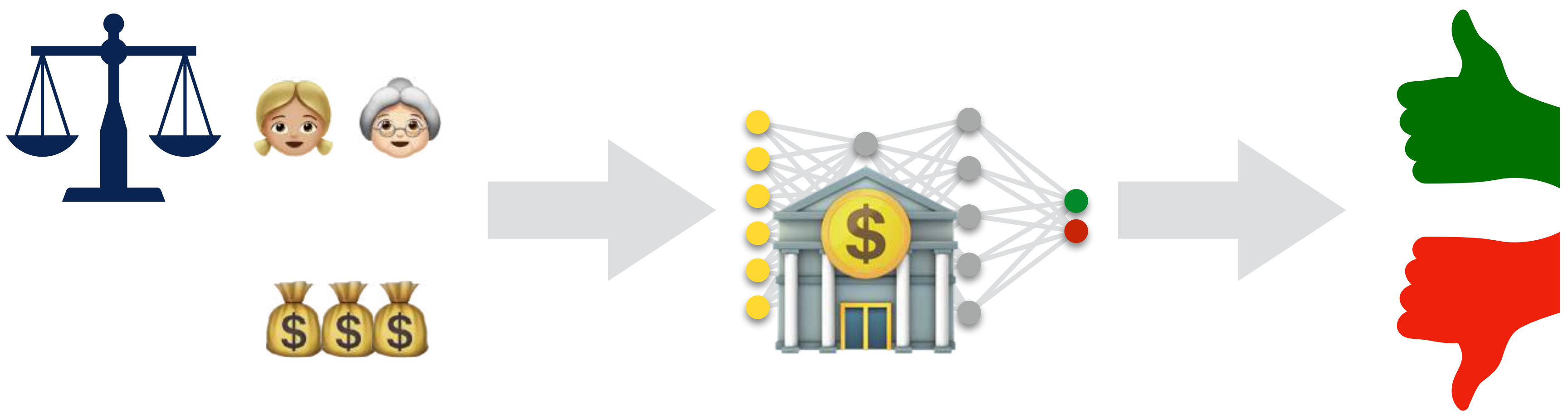
too many disjunctions!

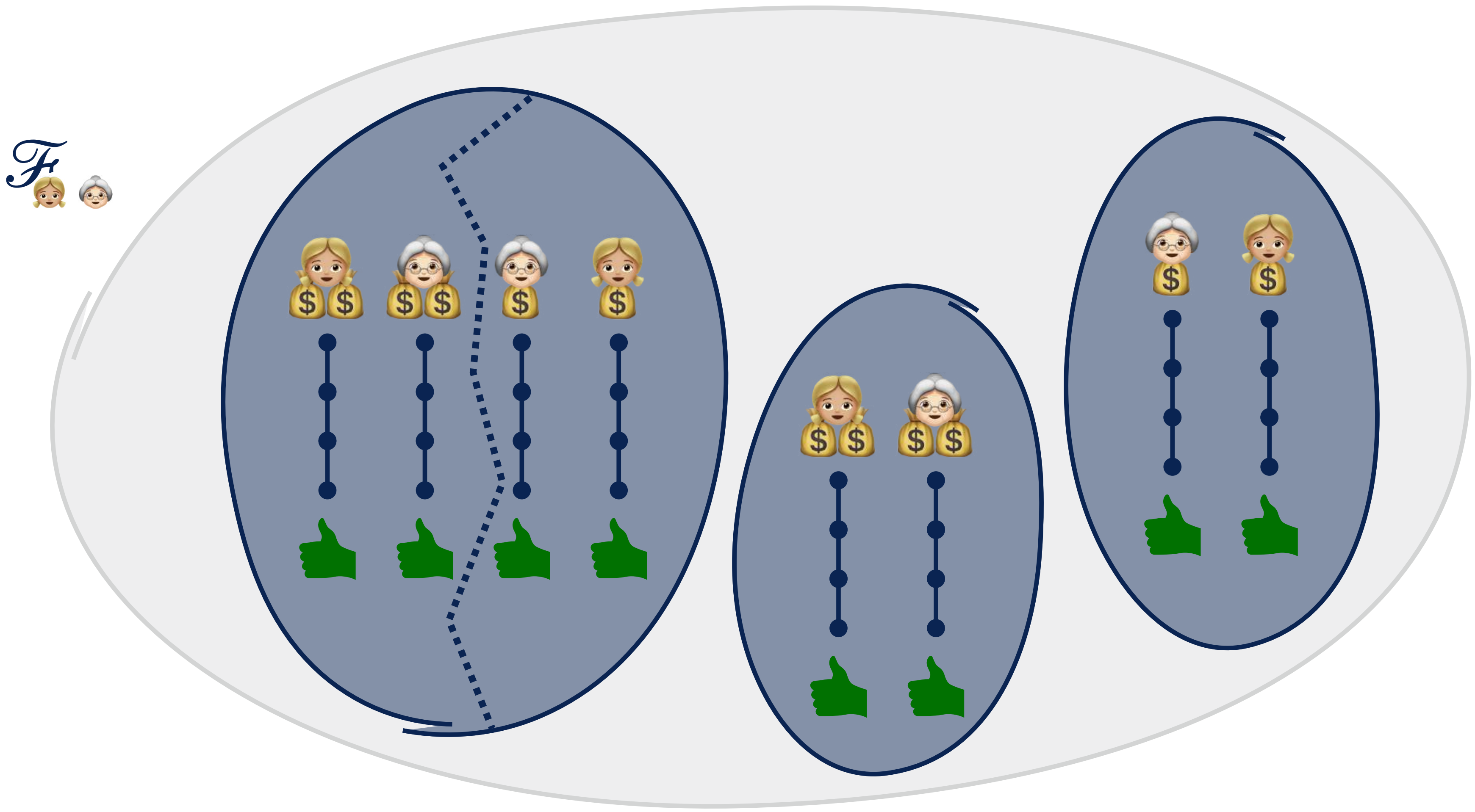
Back to the Semantics…

Hierarchy of Semantics



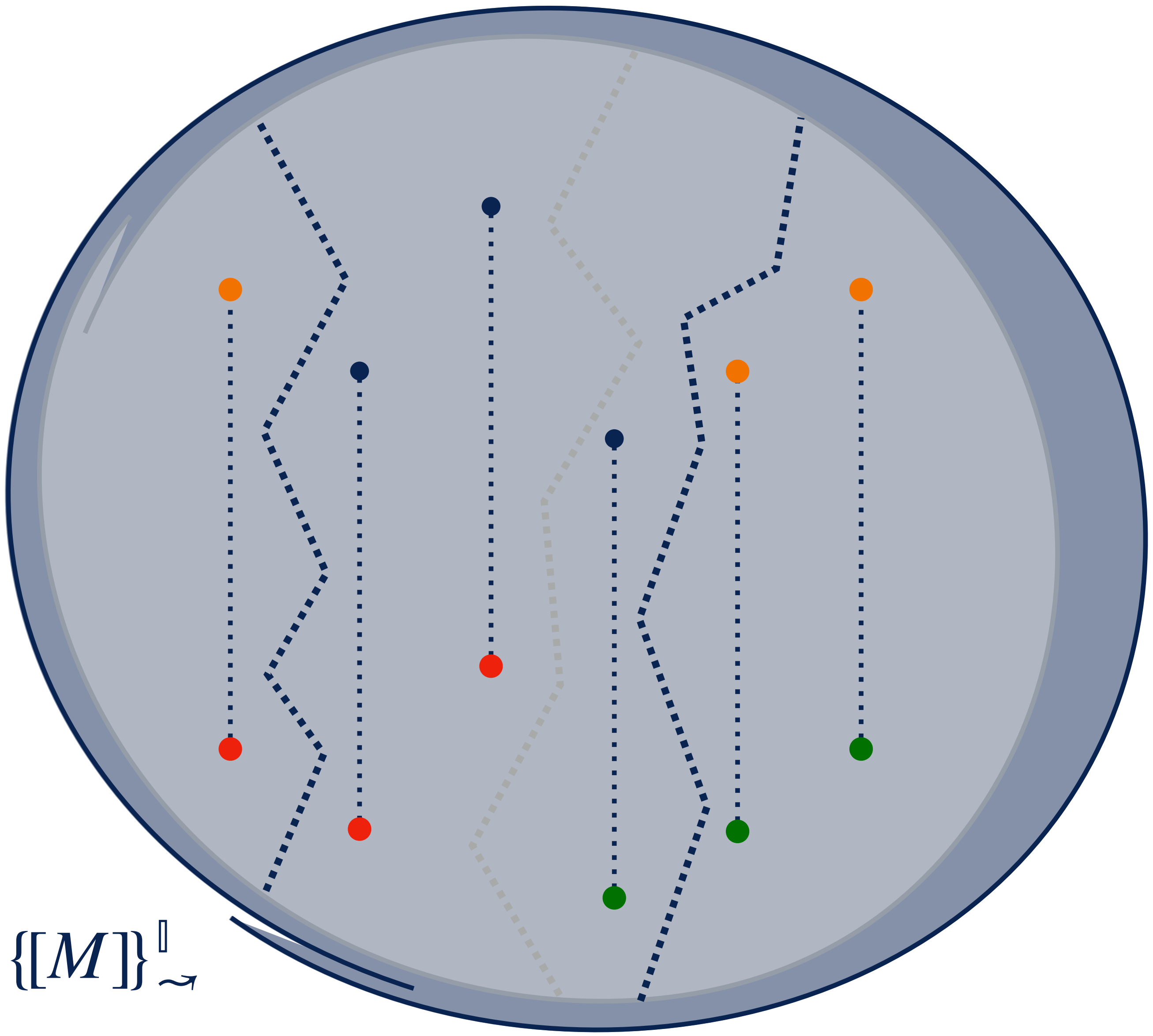
Parallel Semantics





💡 **partitioning** a set of traces that satisfies dependency fairness **with respect to the non-sensitive inputs** yields sets of traces that also satisfy dependency fairness

Parallel Semantics



💡 **partitioning** a set of traces that satisfies dependency fairness **with respect to the non-sensitive inputs** yields sets of traces that also satisfy dependency fairness

Parallel Semantics

$$\begin{tikzcd}
\langle \mathscr{P}(\mathscr{P}(\Sigma \times \Sigma)), \subseteq_{\rightsquigarrow} \rangle \arrow[r, bend right, "\alpha_{\parallel}"'] & \langle \mathscr{P}(\mathscr{P}(\Sigma \times \Sigma)), \subseteq_{\parallel} \rangle \arrow[l, bend right, "\gamma_{\parallel}"']
\end{tikzcd}$$

$$\alpha_{\parallel}(S) \overset{\text{def}}{=} \{\{\langle t_0, t_\omega \rangle \in R \mid t_0 \in I\} \mid R \in S \wedge I \in \mathbb{I}\}$$ **parallel abstraction**

$$\{[M]\}^{\parallel}_{\rightsquigarrow} \overset{\text{def}}{=} \alpha_{\parallel}([\![M]\!]_{\rightsquigarrow})$$
$$= \{\{\langle t_0, t_\omega \rangle \in \Sigma \times \Sigma \mid t \in [\![M]\!] \wedge t_0 \in I \wedge t_\omega \in O\} \mid I \in \mathbb{I} \wedge O \in \mathbb{O}\}$$

Theorem

$$M \models \mathscr{F}_i \Leftrightarrow \gamma_{\rightsquigarrow}(\{[M]\}^{\parallel}_{\rightsquigarrow}) \subseteq \mathscr{F}_i$$

Lemma

$$M \models \mathscr{F}_i \Leftrightarrow \forall I \in \mathbb{I} : \forall A, B \in \{[M]\}^{\parallel}_{\rightsquigarrow} : (A^I_\omega \neq B^I_\omega \Rightarrow A^I_0|_{\neq i} \cap B^I_0|_{\neq i} = \emptyset)$$

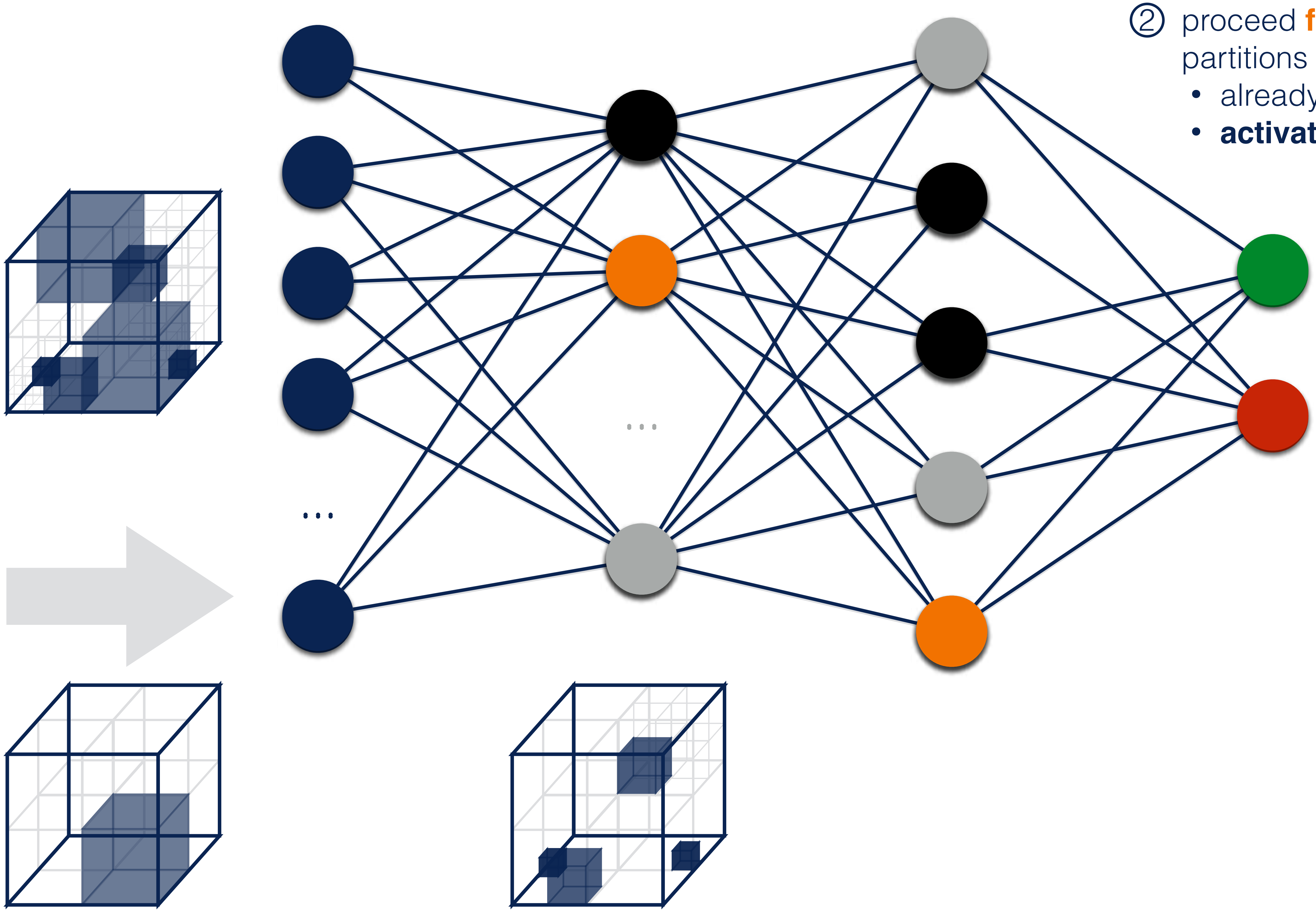
Better Abstraction

Forward and Backward Analysis

① **partition** the space of values of the **non-sensitive input** nodes

② proceed **forwards** from all partitions to find:

- already ✓ **fair** partitions
- **activation patterns**



Forward and Backward Analysis

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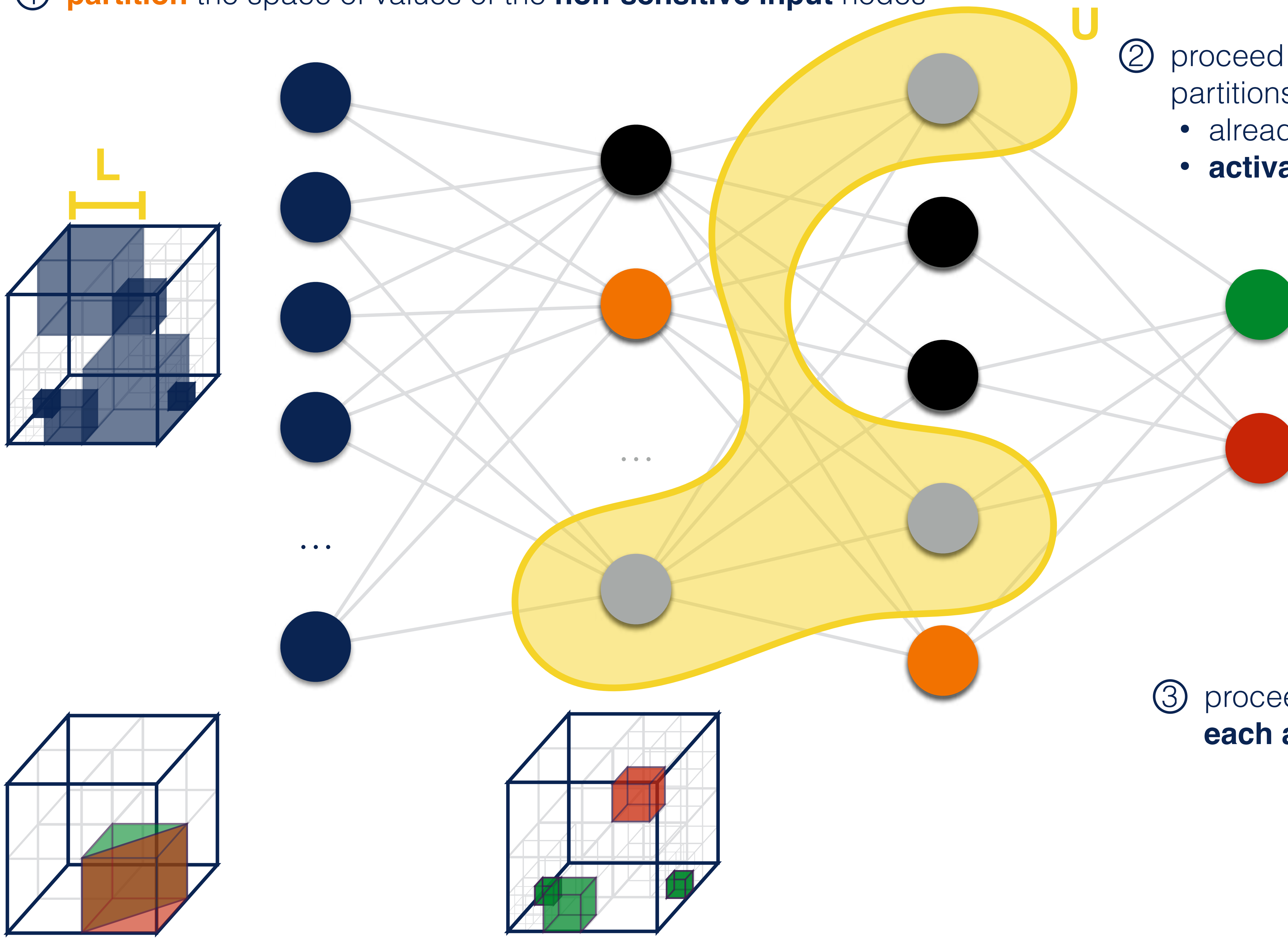

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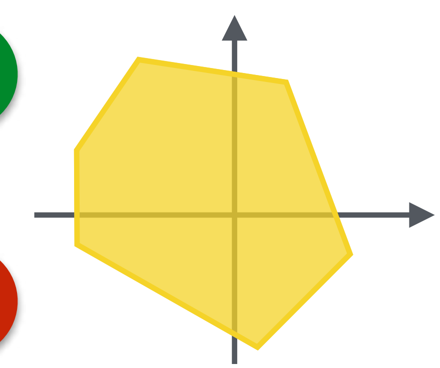
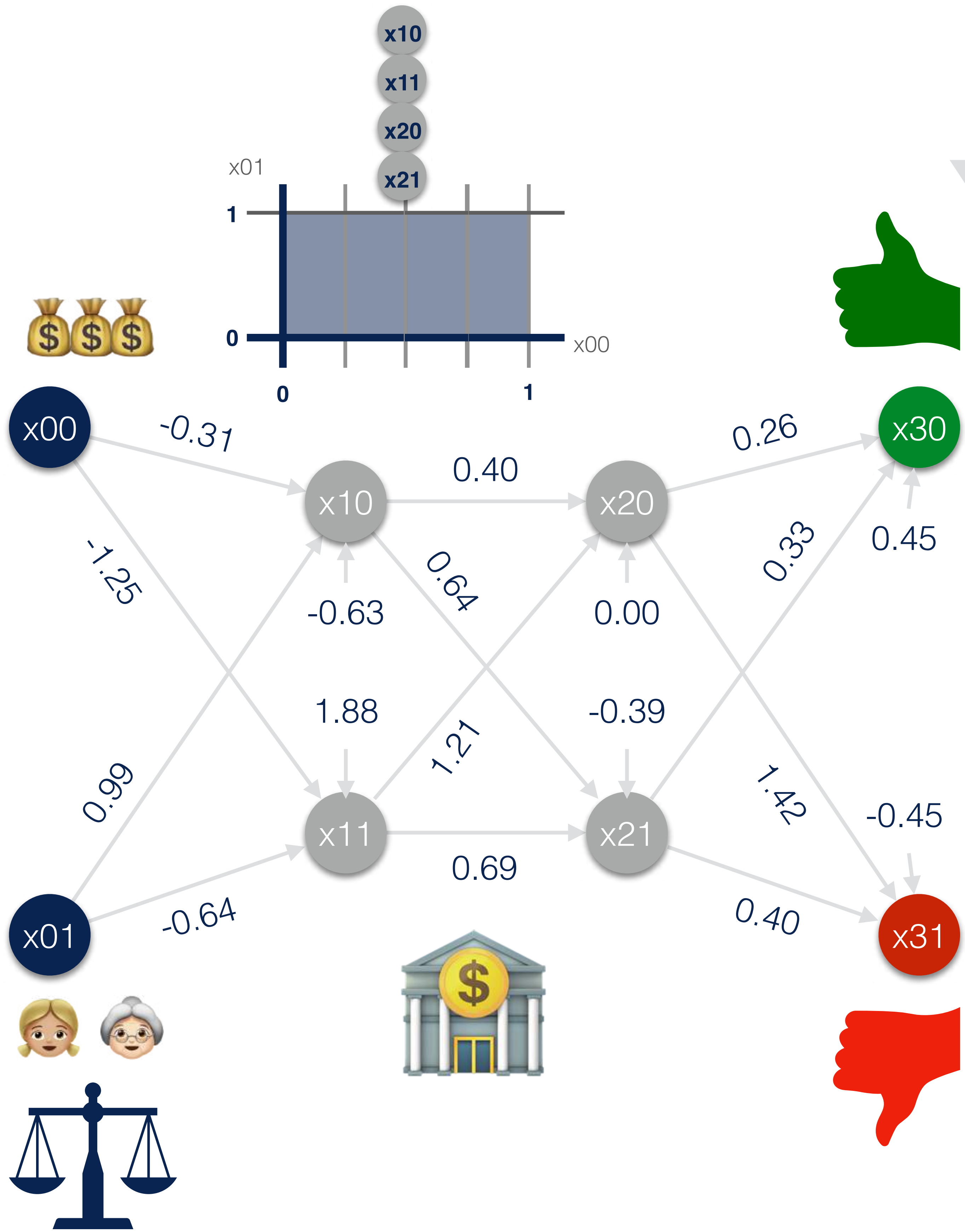


③ proceed **backwards for each activation pattern**



L = 0.25

U = 2

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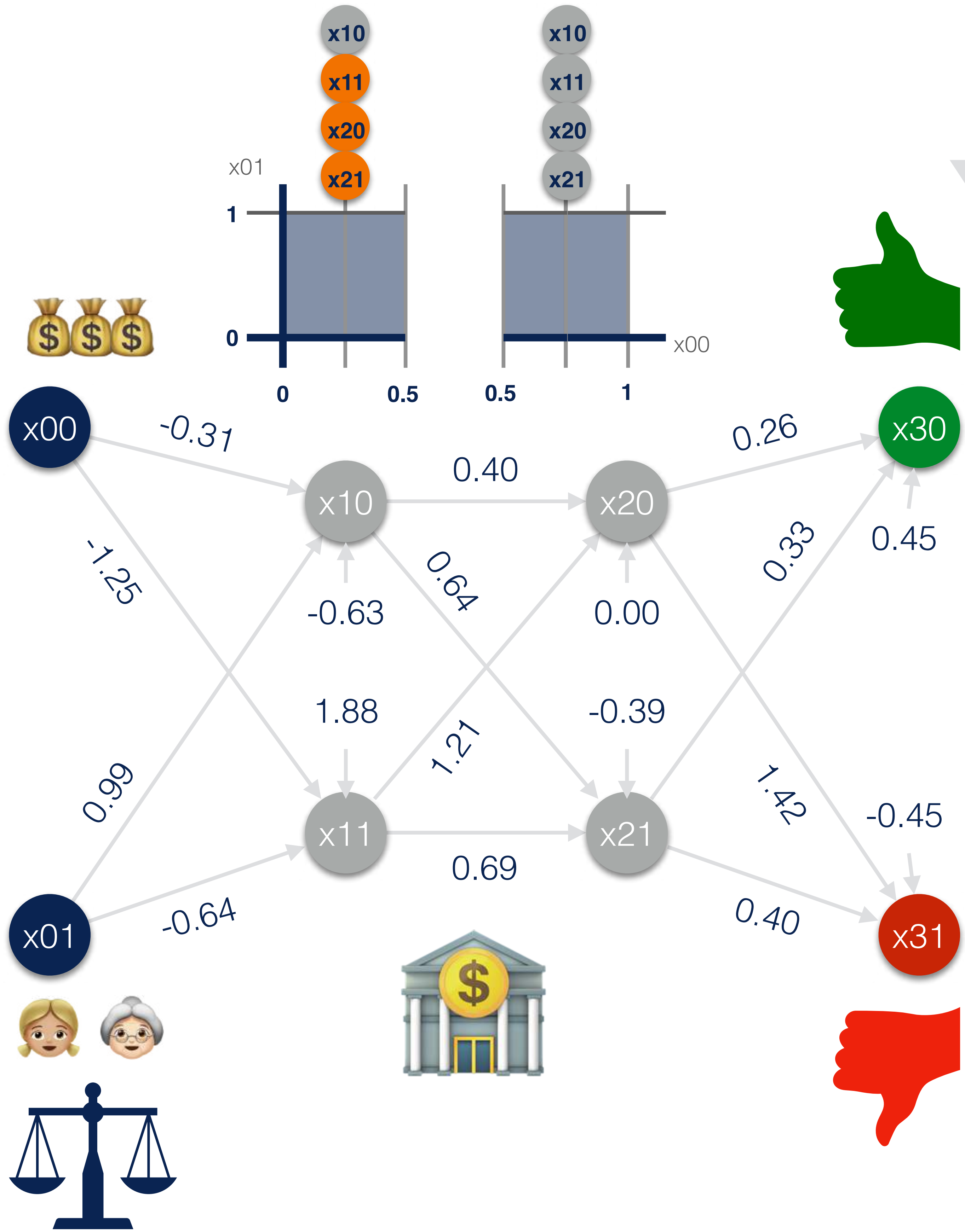
return '👍' if x31 < 30 else '👎'
```



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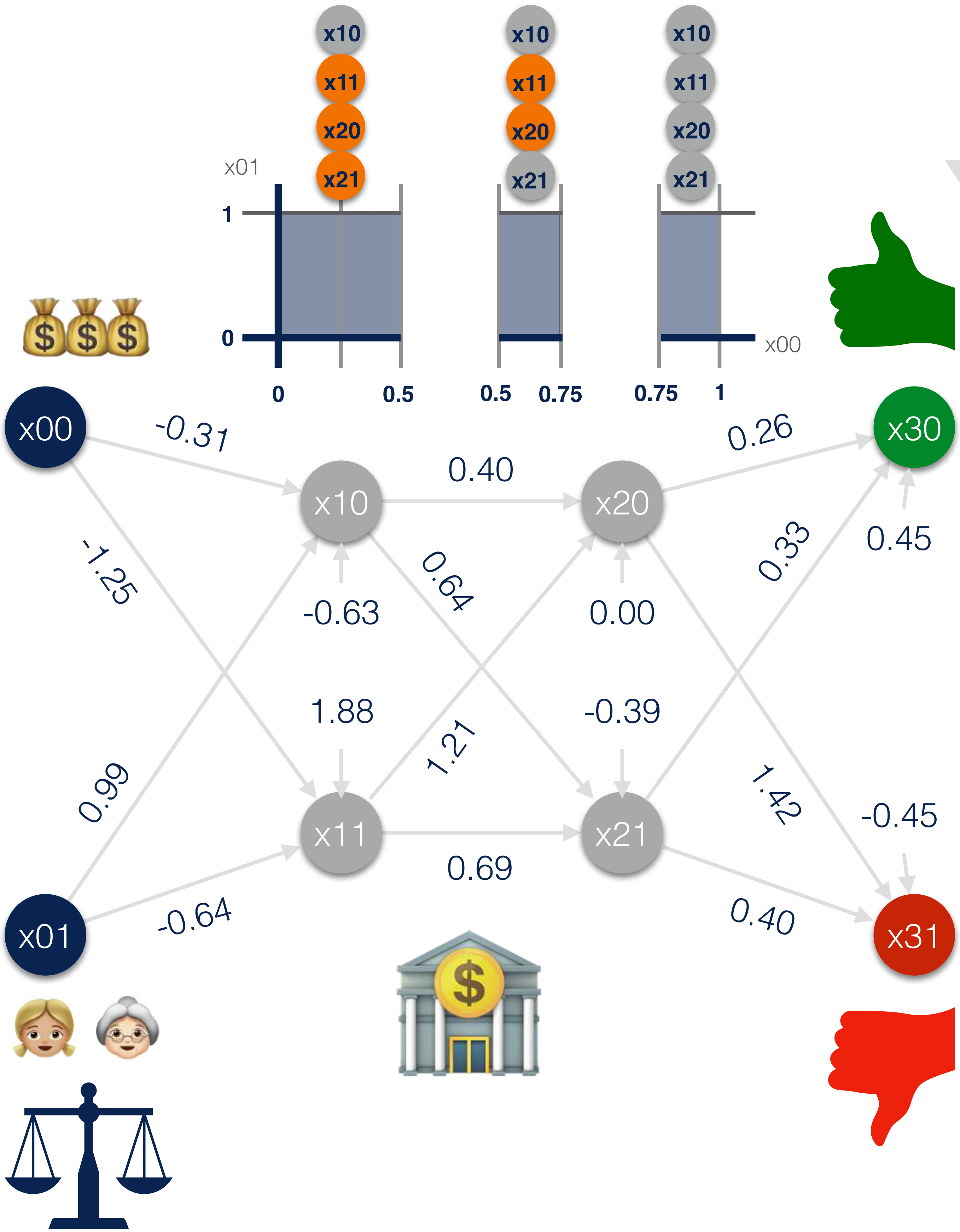

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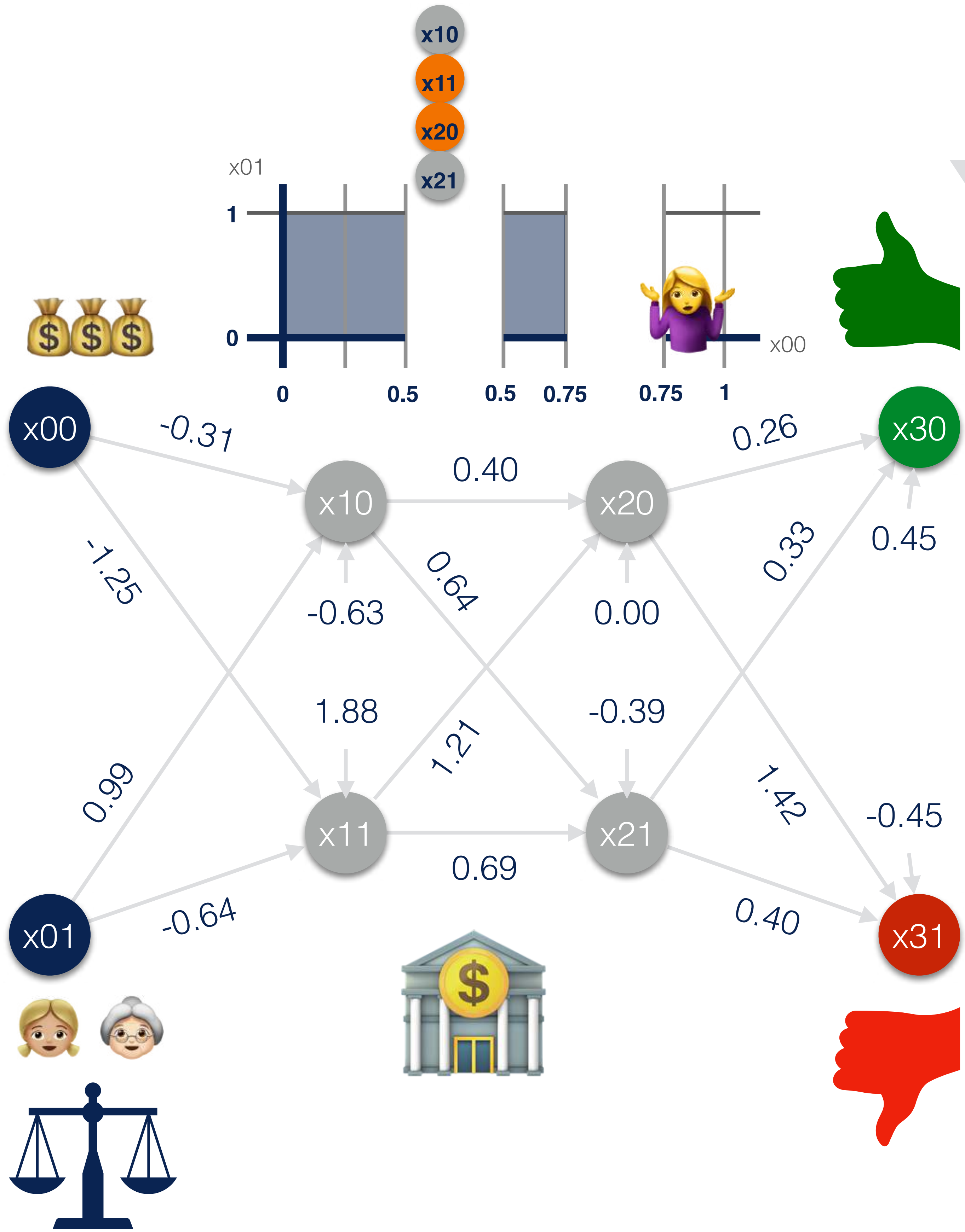

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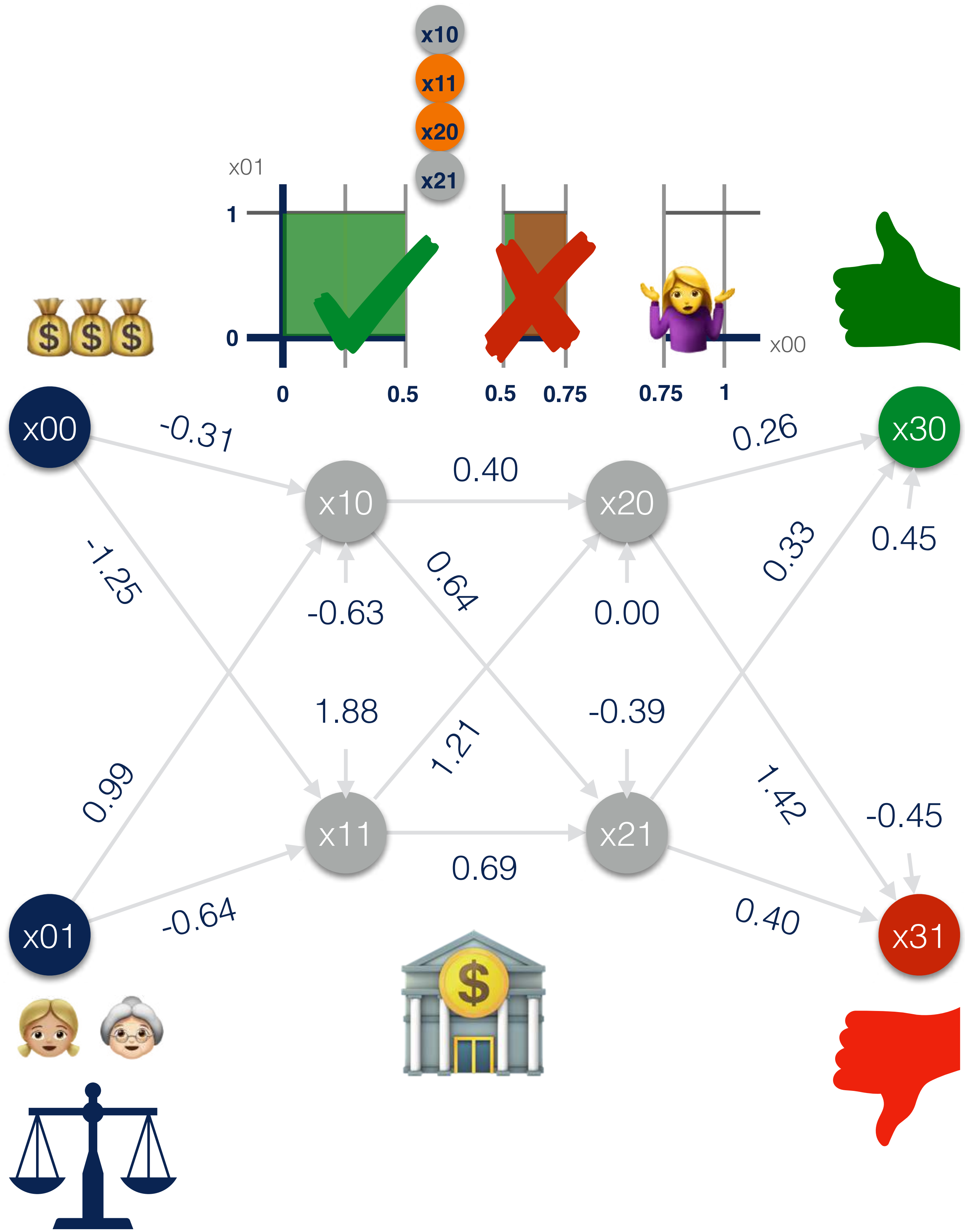

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x30 ≥ x31     x31 ≥ x30
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```

Libra

caterinaurban / **Libra**

Code · Issues · Pull requests · Actions · Projects · Security · Insights

master · **2** branches · **0** tags · Go to file · Code

caterinaurban README · 9f830db on Aug 8 · **53** commits

src	RQ5 and RQ6 reproducibility	4 months ago
.gitignore	RQ1 reproducibility	4 months ago
LICENSE	Initial prototype	2 years ago
README.md	RQ5 and RQ6 reproducibility	4 months ago
README.pdf	README	4 months ago
icon.png	icon	4 months ago
libra.png	icon	4 months ago
requirements.txt	some documentation	4 months ago
setup.py	some documentation	4 months ago

README.md

Libra

Nowadays, machine-learned software plays an increasingly important role in critical decision-making in our social, economic, and civic lives.

About

No description or website provided.

#abstract-interpretation #static-analysis #machine-learning #neural-networks #fairness

Readme

MPL-2.0 License

Releases

No releases published

Packages

No packages published

Languages

- **Python** 98.7%
- **Shell** 1.3%

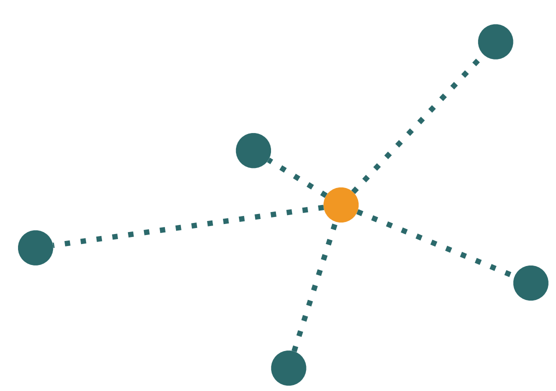
Formal Methods for Model Training

Robust Training

Minimizing the Worst-Case Loss for Each Input

Adversarial Training

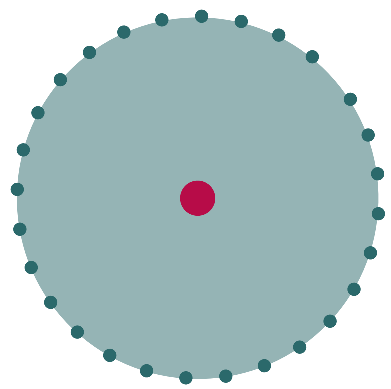
Minimizing a Lower Bound on the Worst-Case Loss for Each Input



generate adversarial inputs
and use them as training data

Certified Training

Minimizing an Upper Bound on the Worst-Case Loss for Each Input



use upper bound as regularizer
to encourage robustness

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