ECE/CS 584: Verification of Embedded and Cyber-physical Systems

Lecture 9: Neural Network Verification with Bound Propagation Algorithms (Part I)

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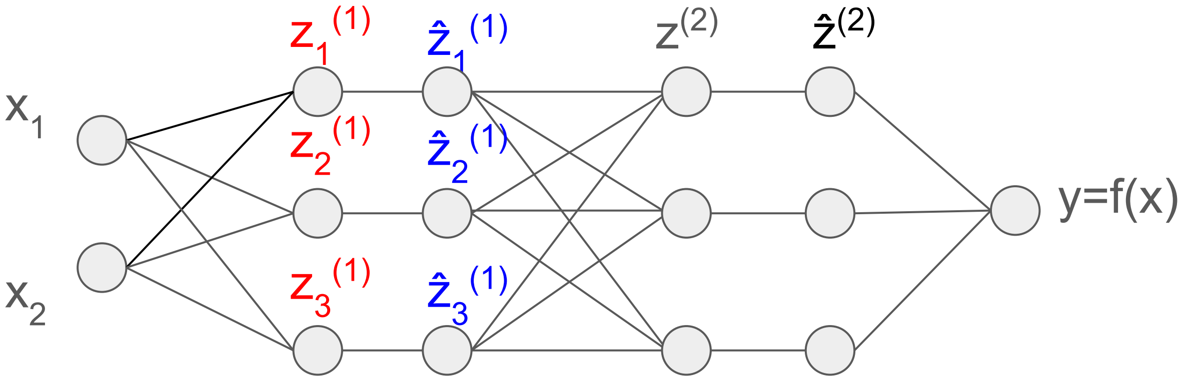
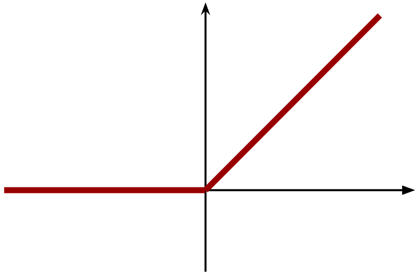
Review: Neural Networks (NNs)

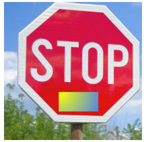


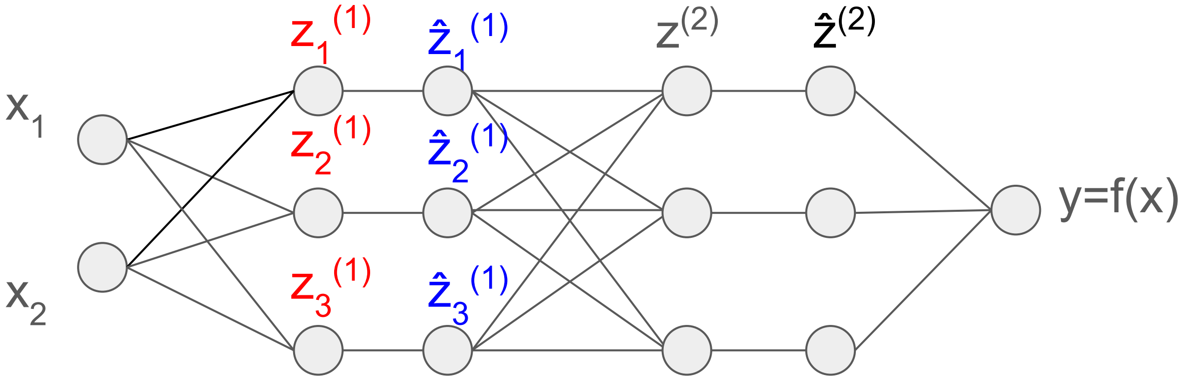


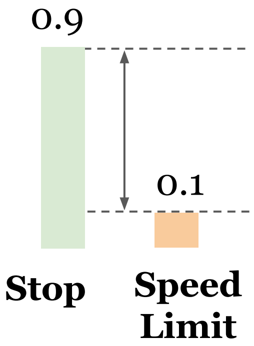
Linear layers: $z^{(1)} = W^{(1)} x$ $\quad z^{(2)} = W^{(2)} \hat{z}^{(1)}$ $\quad y = w^{(3)T} \hat{z}^{(2)}$

Nonlinear layers: $\hat{z}_j^{(i)}=\sigma(z_j^{(i)})$ (assume σ is ReLU for now)

Review: NN verification as an **optimization** problem







$$\exists\ x \in S \ \wedge\ y \leq 0 \ \wedge\ y = f(x)$$

Input domain under consideration

Negation of the desired property

$$y^* = \min_{x \in \mathcal{S}} f(x)$$

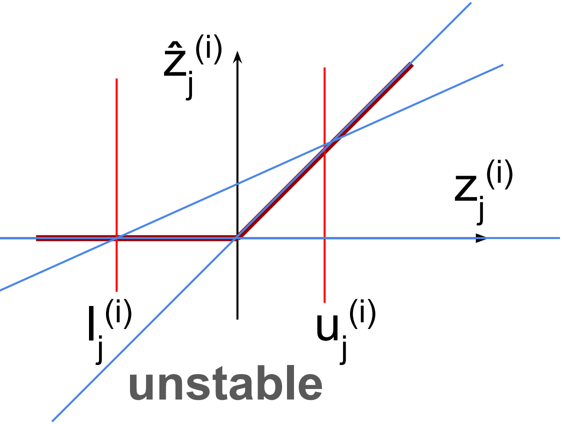
MILP and LP

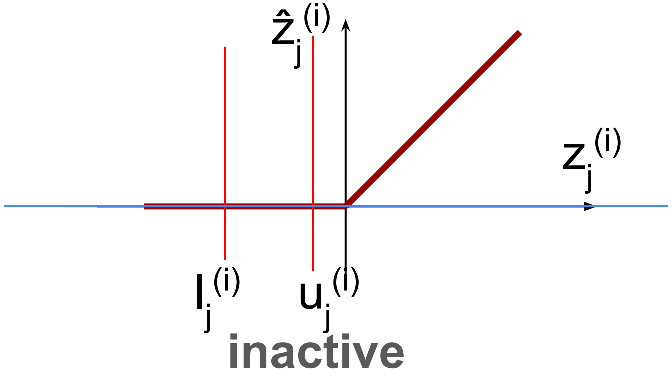
Review: stable vs. unstable neurons

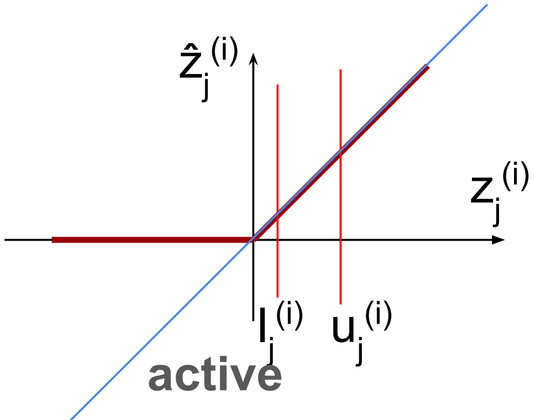
$$\hat{z}_j^{(i)} \leq z_j^{(i)} - l_j^{(i)}(1 - p_j^{(i)})$$
$$\hat{z}_j^{(i)} \leq u_j^{(i)} p_j^{(i)}$$
$$\hat{z}_j^{(i)} \geq z_j^{(i)}$$
$$\hat{z}_j^{(i)} \geq 0$$
$$0 \leq p_j^{(i)} \leq 1$$

$$\hat{z}_j^{(i)} = 0$$

$$\hat{z}_j^{(i)} = z_j^{(i)}$$







Review: triangle relaxation for unstable ReLU neurons

Each ReLU is represented by

$$\hat{z}_j^{(i)} \leq z_j^{(i)} - l_j^{(i)}(1 - p_j^{(i)})$$

$$\hat{z}_j^{(i)} \leq u_j^{(i)} p_j^{(i)}$$

$$\hat{z}_j^{(i)} \geq z_j^{(i)}$$

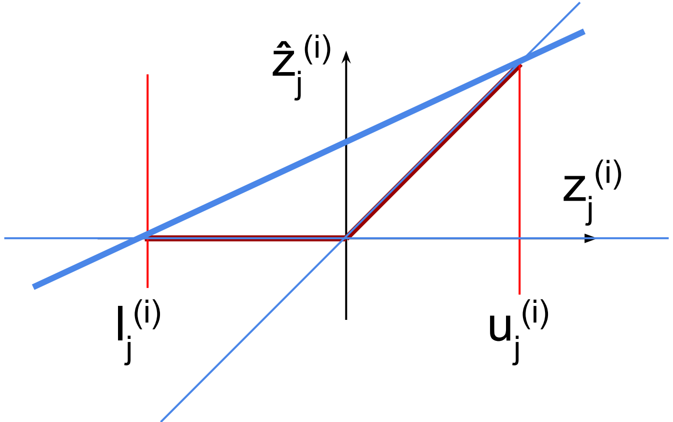
$$\hat{z}_j^{(i)} \geq 0$$

$$\boxed{\hat{z}_j^{(i)} \leq \frac{u_j^{(i)}}{u_j^{(i)} - l_j^{(i)}} z_j^{(i)} - \frac{u_j^{(i)} l_j^{(i)}}{u_j^{(i)} - l_j^{(i)}}}$$

$$\hat{z}_j^{(i)} \geq z_j^{(i)}$$

$$\hat{z}_j^{(i)} \geq 0$$

“Triangle” relaxation



Today: more efficient algorithms for NN verification

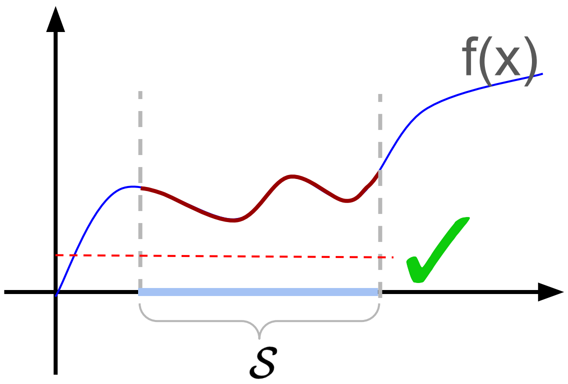
Solving neural network verification using SMT solvers (Lecture 7)

Solving neural network verification using optimization (MIP/LP) (Lecture 8)

Solving neural network verification using **bound propagation (this lecture!)**

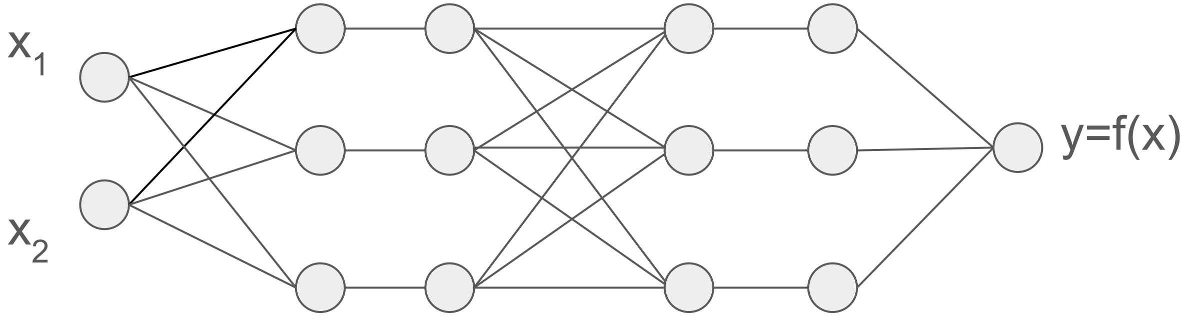
- Interval bound propagation (IBP)
- Linear (symbolic) bound propagation (CROWN)

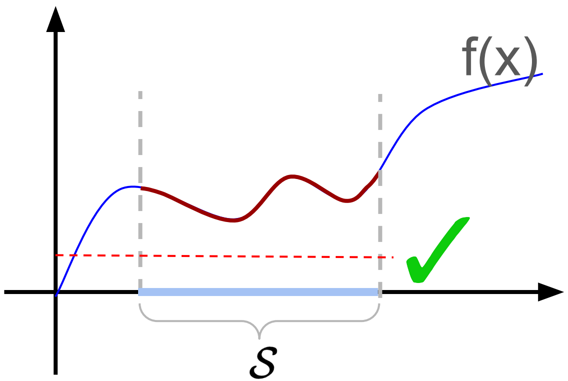
Efficient methods are typically incomplete (solving a lower bound, as tight as possible)



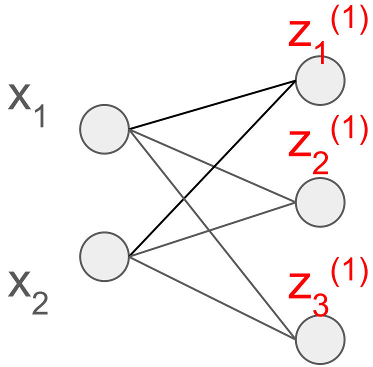
$$y^* = \min_{x \in \mathcal{S}} f(x)$$

Any faster ways to calculate the bounds on f(x)?





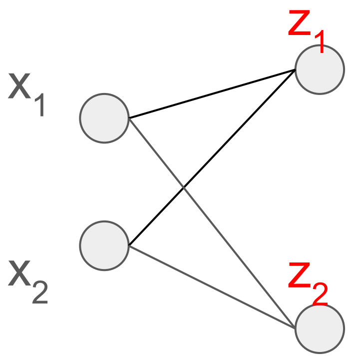
Let's look at one layer first



Given bounds on x, can we calculate the bounds on z?

$$x_1 \in [-1, 2], \; x_2 \in [-2, 1]$$

Let's look at one layer first



Given bounds on x, can we calculate the bounds on z?

$$x_1 \in [-1, 2],\ x_2 \in [-2, 1]$$

As an illustration, suppose we have

$$z_1 = x_1 - x_2$$
$$z_2 = 2x_1 - x_2$$

Can you infer bounds on z given bounds on x?

Interval Bound Propagation (IBP)

$$x_1 \in [-1, 2],\ x_2 \in [-2, 1]$$

$$z_1 = x_1 - x_2$$

$$z_2 = 2x_1 - x_2$$

$$\underline{z}_1 = -1 - 1 = -2$$

$$\overline{z}_1 = 2 - (-2) = 4$$

$$\underline{z}_2 = -1 \times 2 - 1 = -3$$

$$\overline{z}_2 = 2 \times 2 - (-2) = 6$$

Interval Bound Propagation (IBP)

$$x_1 \in [-1, 2],\ x_2 \in [-2, 1] \qquad z_1 = x_1 - x_2 \qquad z_2 = 2x_1 - x_2$$

$$\underline{z}_1 = -1 - 1 = -2 \qquad \overline{z}_1 = 2 - (-2) = 4$$

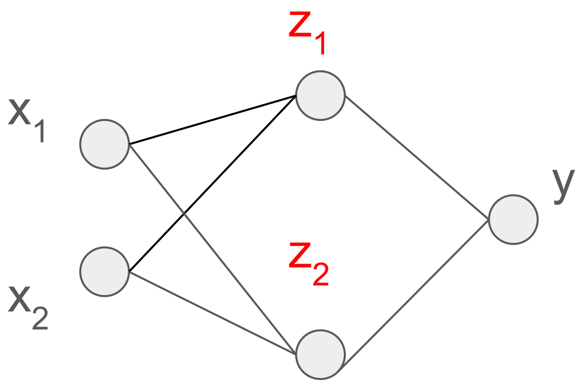
$$\underline{z}_2 = -1 \times 2 - 1 = -3 \qquad \overline{z}_2 = 2 \times 2 - (-2) = 6$$

In general:

$$\sum_{i \in \{i | w_i \geq 0\}} w_i l_i + \sum_{i \in \{i | w_i < 0\}} w_i u_i \leq \sum_i w_i x_i \leq \sum_{i \in \{i | w_i \geq 0\}} w_i u_i + \sum_{i \in \{i | w_i < 0\}} w_i l_i$$

Elements lower and upper bounds of x

Interval Bound Propagation: continue to the next layer



Let's say $y = z_1 - z_2$

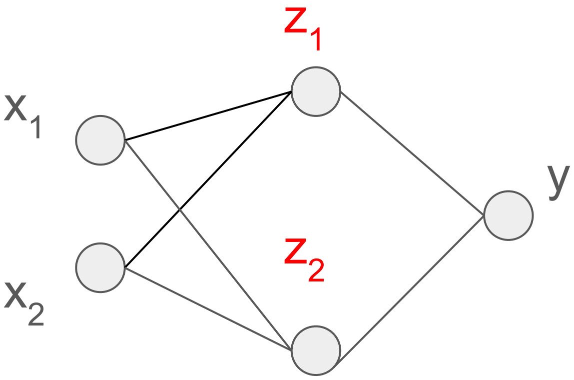
We also know that:

$$z_1 \in [\mathbf{-2, 4}] \qquad z_2 \in [\mathbf{-3, 6}]$$

The what can we conclude about y?

$$y \in [\mathbf{-8, 7}]$$

Interval Bound Propagation: limitations



Apply IBP we obtain $y \in [-8, 7]$ for this simple linear network.

However observe that

$$z_1 = x_1 - x_2$$
$$z_2 = 2x_1 - x_2$$
$$y = z_1 - z_2$$
$$y = x_1 - x_2 - (2x_1 - x_2) = -x_1$$

The actual bounds is [-2, 1], much tighter than [-8, 7]

A Better Idea: Keep the correlations between x and z

$$z_1 = x_1 - x_2$$
$$z_2 = 2x_1 - x_2$$
$$y = z_1 - z_2$$
$$y = x_1 - x_2 - (2x_1 - x_2) = -x_1$$

The actual bounds is [-2, 1], much tighter than [-8, 7]

It is important to keep the correlations between z and x to obtain this tighter result!

We treat z as a **symbolic function of x**, rather than intervals

A Better Idea: linear bound propagation

$$z_1 = x_1 - x_2$$
$$z_2 = 2x_1 - x_2$$
$$y = z_1 - z_2$$
$$y = x_1 - x_2 - (2x_1 - x_2) = -x_1$$

The actual bounds is [-2, 1], much tighter than [-8, 7]

It is important to keep the correlations between z and x to obtain this tighter result!

We treat z as a **linear function of x**, rather than intervals

A Better Idea: linear bound propagation

$$y = z_1 - z_2 \xrightarrow{\text{Plug in}} y = x_1 - x_2 - (2x_1 - x_2) = -x_1$$

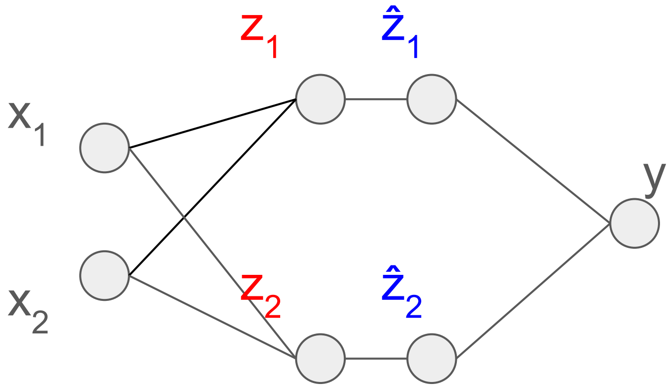
Plug in

$$z_1 = x_1 - x_2$$
$$z_2 = 2x_1 - x_2$$

We treat z as a **linear function of x**, rather than concrete intervals.

After we plug in linear functions (z w.r.t. x), we still get a linear function (y w.r.t. x)

Bound propagation: how about nonlinear functions?



Instead of $y = z_1 - z_2$

Now we have $y = \text{ReLU}(z_1) - \text{ReLU}(z_2)$

From IBP we already know that

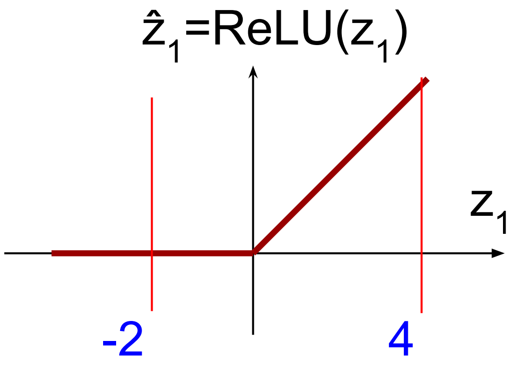
$z_1 \in [-2, 4]$, $z_2 \in [-3, 6]$,

$\text{ReLU}(z_1) \in [0, 4]$, $\text{ReLU}(z_1) \in [0, 6]$

$y \in [-6, 4]$

Can we improve IBP using symbolic linear bounds?

Linear bound propagation for ReLU function (CROWN)



Instead of $y = z_1 - z_2$

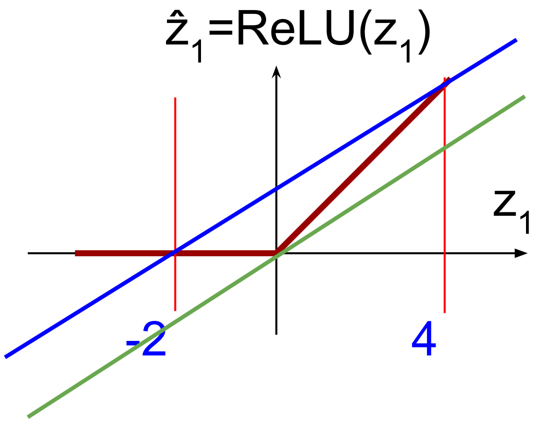
Now we have $y = \mathrm{ReLU}(z_1) - \mathrm{ReLU}(z_2)$

We already know that

$z_1 \in [-2, 4]$, $z_2 \in [-3, 6]$,

(Preactivation bounds)

Linear bound propagation for ReLU function (CROWN)

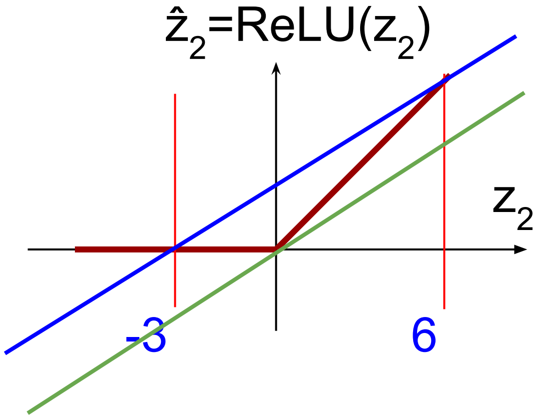


Linear upper bound (same as the one of triangle relaxation in LP)

Linear lower bound (actually not unique)

$$\boxed{\frac{2}{3} z_1} \leq \mathrm{ReLU}(z_1) \leq \boxed{\frac{2}{3} z_1 + \frac{4}{3}}$$

Linear bound propagation for ReLU function (CROWN)



ReLU(z_2) can be bounded using linear functions similarly.

Now let's consider y = ReLU(z_1) - ReLU(z_2). How to bound it using linear functions of z_1 and z_2?

$$\frac{2}{3}z_1 \le \mathrm{ReLU}(z_1) \le \frac{2}{3}z_1 + \frac{4}{3}$$

$$\frac{2}{3}z_2 \le \mathrm{ReLU}(z_2) \le \frac{2}{3}z_2 + 2$$

Linear bound propagation for ReLU function (CROWN)

$$\boxed{\frac{2}{3}z_1} \le \mathrm{ReLU}(z_1) \le \frac{2}{3}z_1 + \frac{4}{3} \qquad \frac{2}{3}z_2 \le \mathrm{ReLU}(z_2) \le \boxed{\frac{2}{3}z_2 + 2}$$

Negative coefficient, take upper bound

$$\boxed{\frac{2}{3}z_1} - \boxed{\left(\frac{2}{3}z_2 + 2\right)} \le$$

positive coefficient, take lower bound

$$y = \mathrm{ReLU}(z_1) - \mathrm{ReLU}(z_2)$$

$$\le \left(\frac{2}{3}z_1 + \frac{4}{3}\right) - \frac{2}{3}z_2$$

Linear bound propagation for ReLU function (CROWN)

$$\frac{2}{3}z_1 - \left(\frac{2}{3}z_2 + 2\right) \leq y \leq \left(\frac{2}{3}z_1 + \frac{4}{3}\right) - \frac{2}{3}z_2$$

Now we have linear inequalities for y w.r.t. z!

Next step we can simply plug in, as in the linear ($y=z_1-z_2$) case.

Linear bound propagation for ReLU function (CROWN)

$$\frac{2}{3}z_1 - (\frac{2}{3}z_2 + 2) \leq y \leq (\frac{2}{3}z_1 + \frac{4}{3}) - \frac{2}{3}z_2$$

$$z_1 = x_1 - x_2$$
$$z_2 = 2x_1 - x_2$$

$\Downarrow$ Plug in

$$-\frac{2}{3}x_1 - 2 \leq y \leq -\frac{2}{3}x_1 + \frac{4}{3}$$

Linear bound propagation for ReLU function (CROWN)

We now have symbolic linear bounds for y w.r.t. x

$$\boxed{-\frac{2}{3}x_1 - 2} \le y \le \boxed{-\frac{2}{3}x_1 + \frac{4}{3}}$$

$$x_1 \in [-1, 2],\ x_2 \in [-2, 1]$$

Take lower bound given x

Take upper bound given x

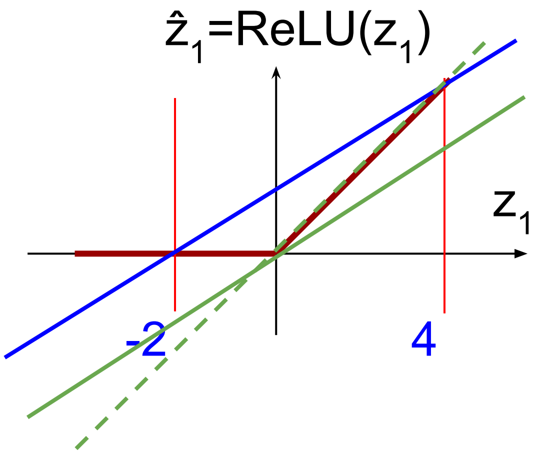
$$y \in [-\frac{10}{3}, 2]$$

Concrete interval bounds

A lot more tighter than IBP bounds y ∈ [-6, 4]

Can we do even better?

Let’s recall that when we linearly bound the ReLU function, there are some flexibilities



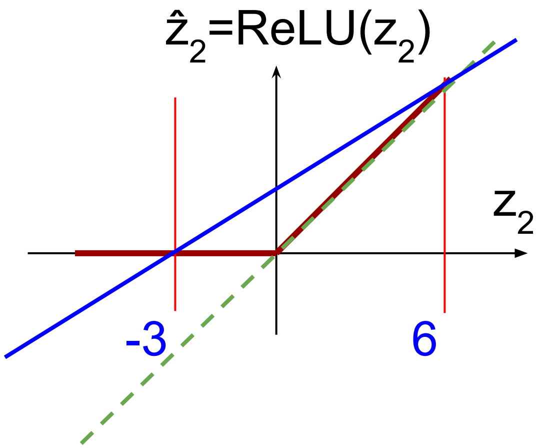
Linear upper bound (same as the one of triangle relaxation in LP)

Linear lower bound (actually not unique)

$$\frac{2}{3}z_1 \leq \mathrm{ReLU}(z_1) \leq \frac{2}{3}z_1 + \frac{4}{3}$$

Also valid: $\boxed{z_1} \leq \mathrm{ReLU}(z_1) \leq \frac{2}{3}z_1 + \frac{4}{3}$

Choosing different linear bounds (α-CROWN)



Now what are the linear bounds of
y = ReLU(z_1) - ReLU(z_2)?

$$z_1 - \left(\frac{2}{3}z_2 + 2\right) \leq y \leq \left(\frac{2}{3}z_1 + \frac{4}{3}\right) - z_2$$

$$z_1 \leq \mathrm{ReLU}(z_1) \leq \frac{2}{3}z_1 + \frac{4}{3}$$

$$z_2 \leq \mathrm{ReLU}(z_2) \leq \frac{2}{3}z_2 + 2$$

Choosing different linear bounds (α-CROWN)

$$z_1 - (\tfrac{2}{3}z_2 + 2) \leq y \leq (\tfrac{2}{3}z_1 + \tfrac{4}{3}) - z_2$$

$$z_1 = x_1 - x_2$$

$$z_2 = 2x_1 - x_2$$

Plug in

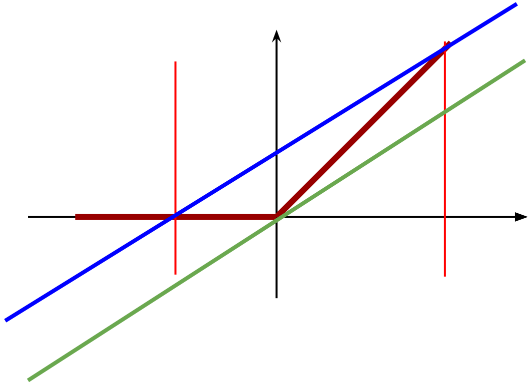
$$-\tfrac{1}{3}x_1 - \tfrac{1}{3}x_2 - 2 \leq y \leq -\tfrac{4}{3}x_1 + \tfrac{1}{3}x_2 + \tfrac{4}{3}$$

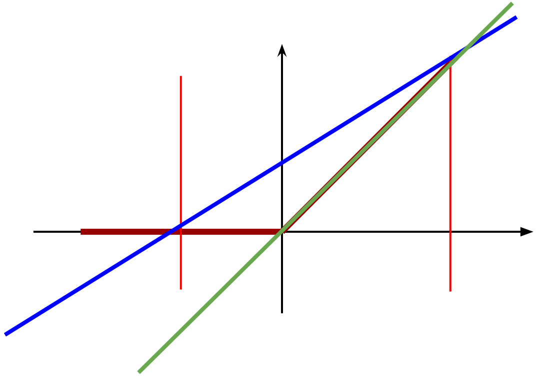
$$x_1 \in [-1, 2],\ x_2 \in [-2, 1]$$

Concretize

$$y \in [-3, 3]$$

Linear lower bounds for ReLU function matters!





$$\frac{2}{3}z_1 \leq \mathrm{ReLU}(z_1) \leq \frac{2}{3}z_1 + \frac{4}{3}$$

$$\frac{2}{3}z_2 \leq \mathrm{ReLU}(z_2) \leq \frac{2}{3}z_2 + 2$$

$$y \in [-\frac{10}{3}, 2]$$

$$z_1 \leq \mathrm{ReLU}(z_1) \leq \frac{2}{3}z_1 + \frac{4}{3}$$

$$z_2 \leq \mathrm{ReLU}(z_2) \leq \frac{2}{3}z_2 + 2$$

$$y \in [-3, 3]$$

Which one is correct?

Linear lower bounds for ReLU function matters!

Both results are correct! But we want the bounds to be as tight as possible! So best result is **$y \in [-3, 2]$**

In general, the slope of the linear lower bound for every ReLU neuron can be optimized to find the best result.

Linear lower bounds for ReLU function matters!

In general, the slope of the linear lower bound for every ReLU neuron can be optimized to find the best result.

$$\alpha_1 z_2 \leq \mathrm{ReLU}(z_2) \leq \frac{2}{3} z_2 + \frac{4}{3}$$

$$\alpha_2 z_2 \leq \mathrm{ReLU}(z_2) \leq \frac{2}{3} z_2 + 2$$

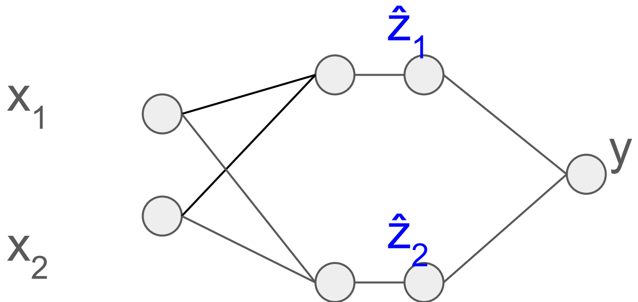
For optimal lower bound of y, set $\alpha_1=1$, $\alpha_2=1$

For optimal upper bound of y, set $\alpha_1=⅔$, $\alpha_2=⅔$

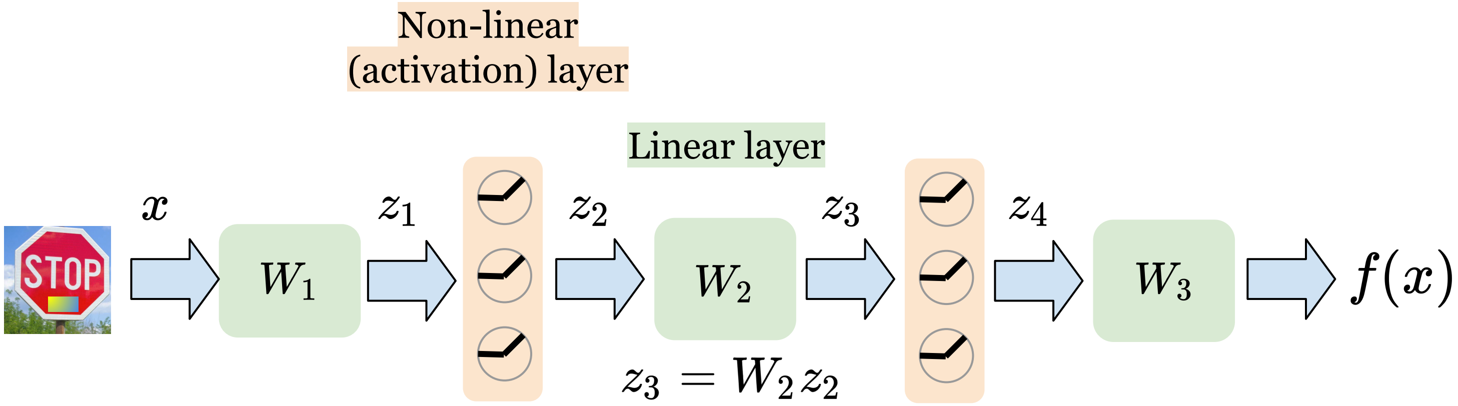
(note that the optimal α_1 and α_2 do not equal in general)

Linear bound propagation method (CROWN)

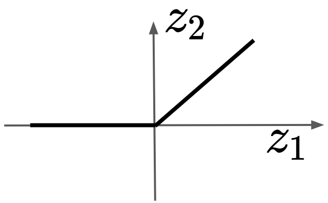
1. Obtain all pre-activation bounds (can be done via CROWN recursively)
2. Start from the output layer, form the initial linear (in)equality y = y
3. Recursively propagate linear inequality y <= $a^Tz + b$ through each layer:
    a. For a linear layer, z=Wz', directly plug in $a^Tz + b$ to get a linear bound of z'
    b. For a non-linear layer (e.g., z=ReLU(z')), we first form the linear inequalities to bound the nonlinear layer itself. Then multiply either the lower or upper bound based on the sign of element in a
4. When the linear inequality propagates to the input layer, we can concretize the linear bound using bounds on input layer.



How to propagate the linear bounds?



$$z_2 = \text{ReLU}(z_1)$$

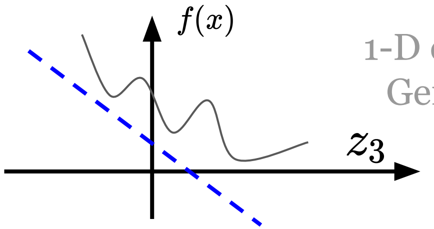


Steps:

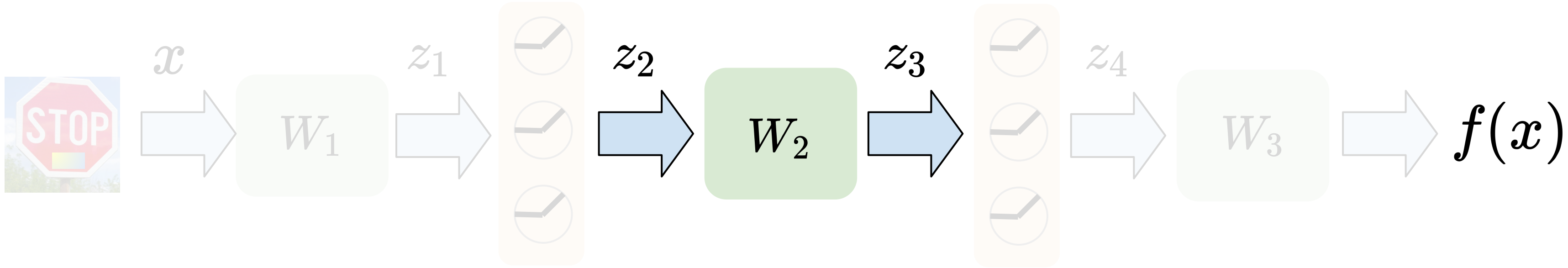
- Propagate bounds through linear layers
- Propagate bounds through non-linear layers

What linear inequalities to propagate?

A linear lower bound for an intermediate layer

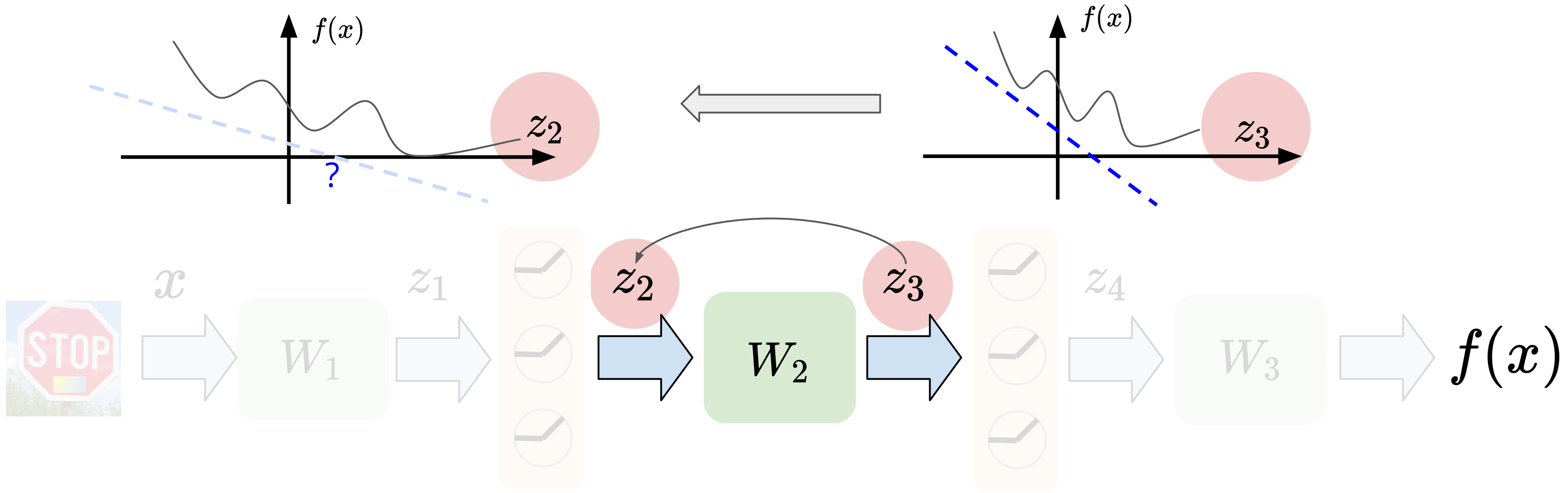


1-D case for illustration. Generally it's a linear hyperplane



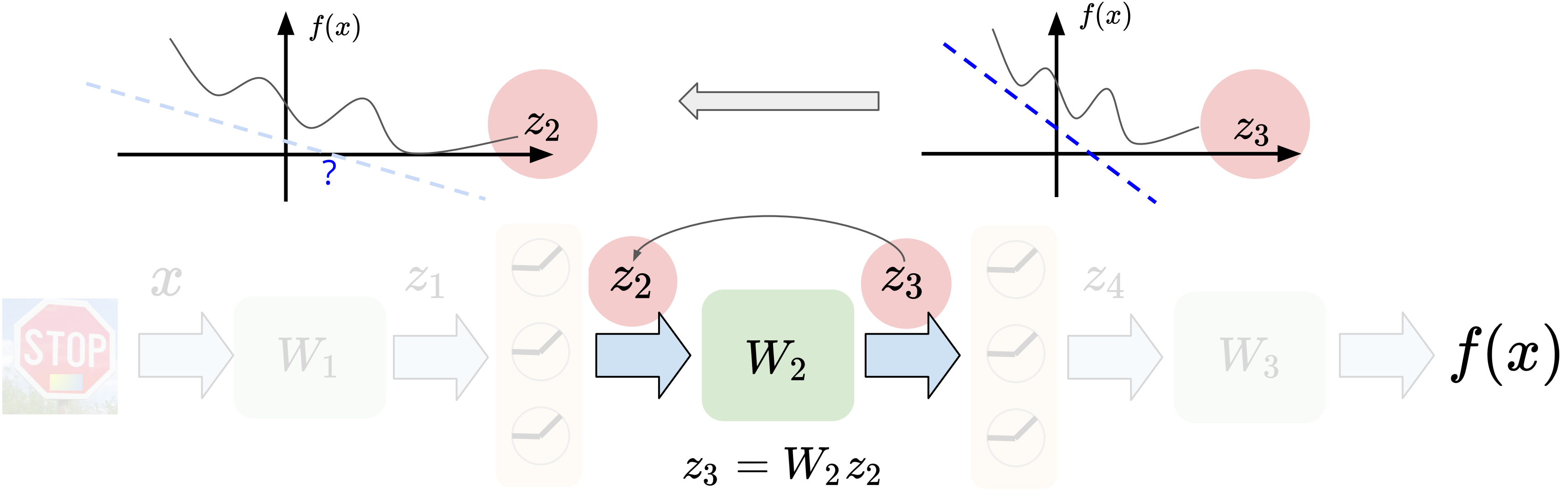
$$f(x) \geq a^\top z_3 + b$$

CROWN: propagating bounds through **linear** layers



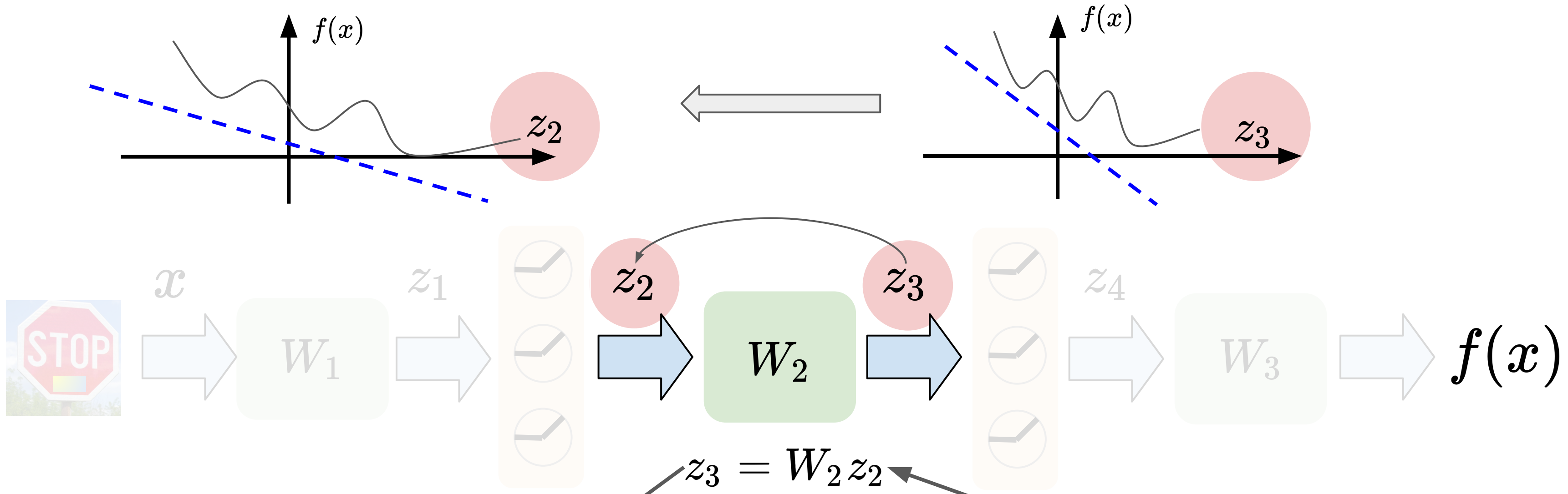
Propagate it to one layer before,
while keeping the lower bound valid

CROWN: propagating bounds through **linear** layers



$$f(x) \geq a^\top z_3 + b$$

CROWN: propagating bounds through **linear** layers

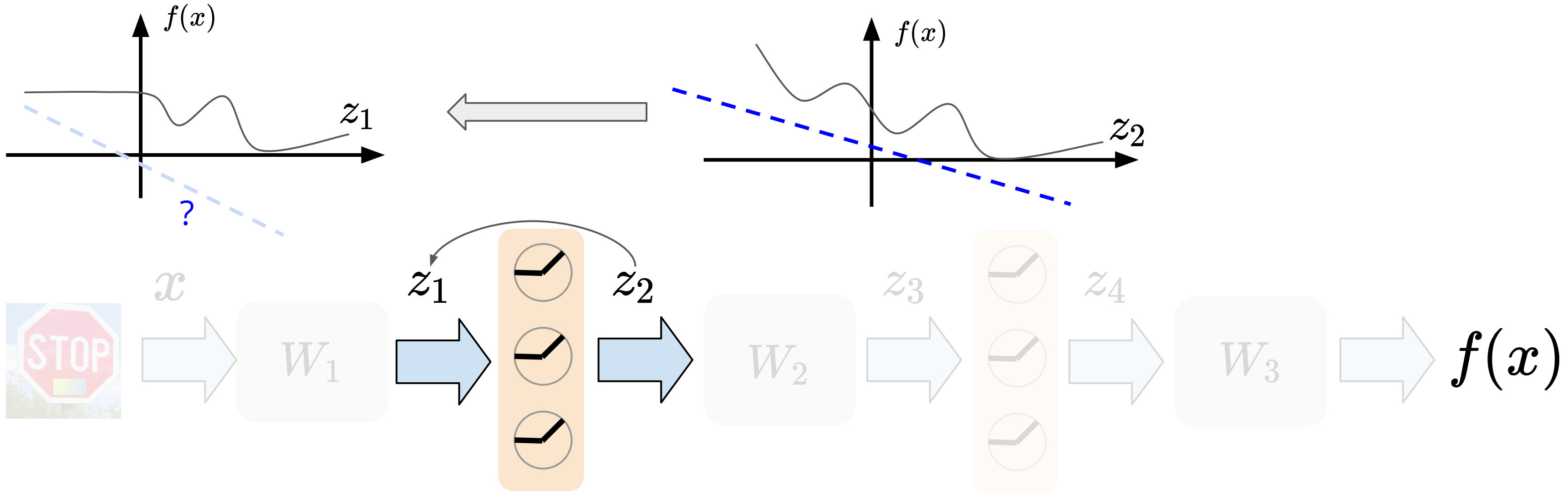


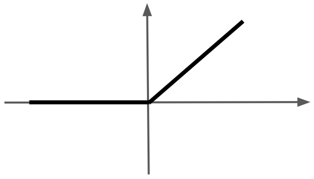
$$z_3 = W_2 z_2$$

$$f(x) \geq a^\top W_2 z_2 + b \qquad \qquad f(x) \geq a^\top z_3 + b$$

Inequality updated after propagation

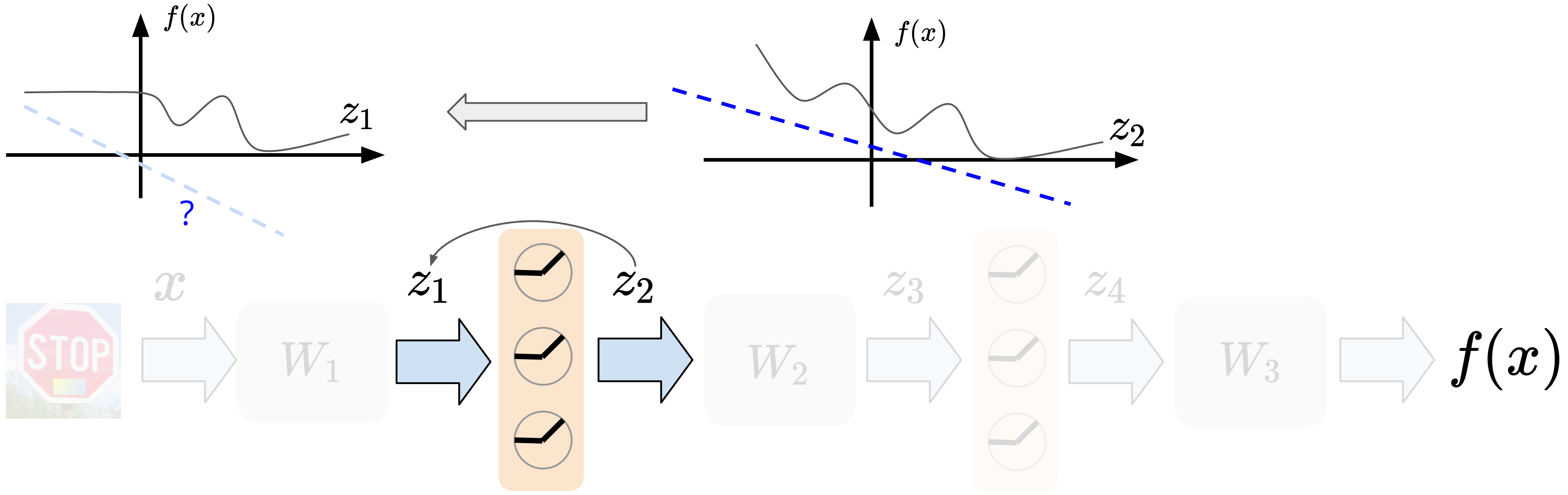
CROWN: propagating bounds through **non-linear** layers





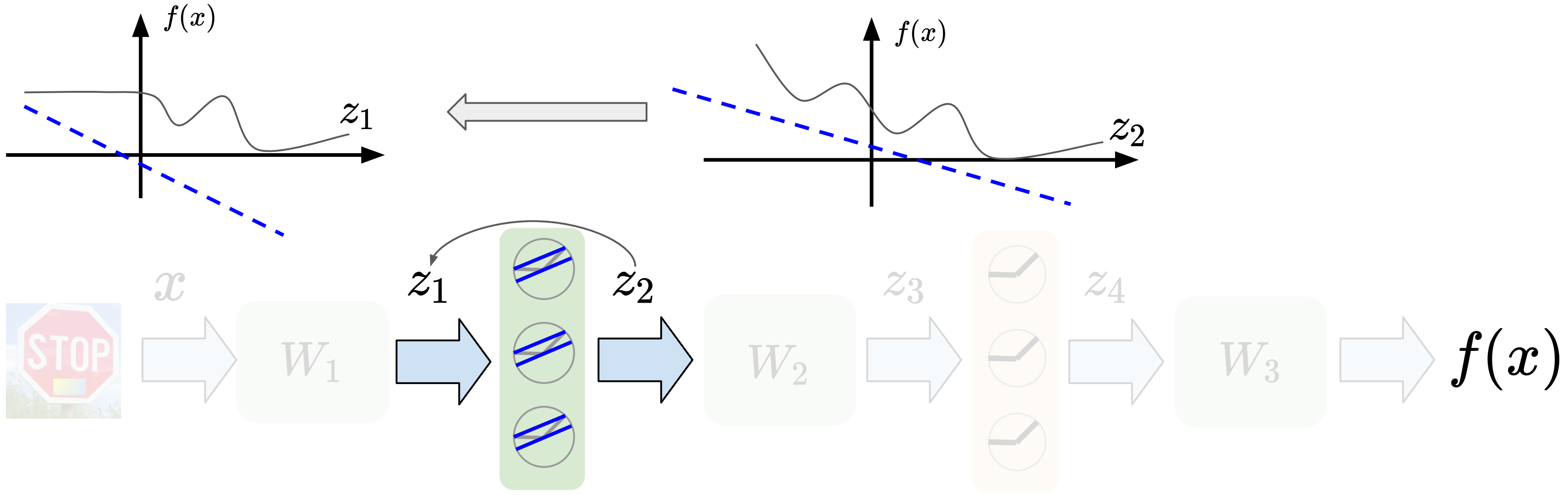
ReLU is NOT a simple linear function

CROWN: propagating bounds through **non-linear** layers



$$f(x) \geq a^\top W_2 z_2 + b \quad \forall x \in \mathcal{S}$$

CROWN: propagating bounds through **non-linear** layers



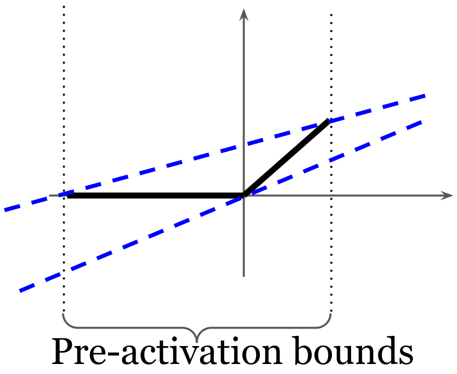
Theorem (informal): we can efficiently find $D,\ b'$ such that:

$$f(x) \geq a^\top W_2 D z_1 + b' \Longleftarrow f(x) \geq a^\top W_2 z_2 + b \quad \forall x \in \mathcal{S}$$

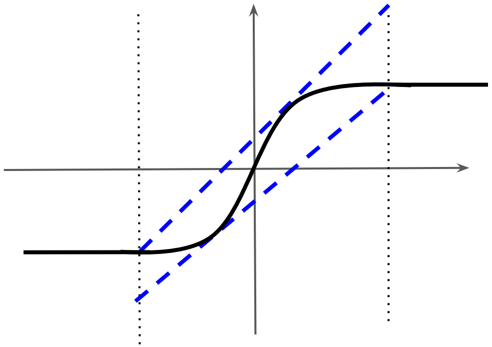
[**Z***W*CHD NeurIPS 2018]

CROWN: propagating bounds through **non-linear** layers

Proof sketch: conservatively use linear bounds to replace a non-linear function.



(can be pre-computed using CROWN)



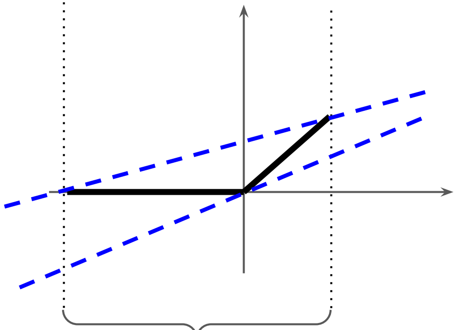
Theorem (informal): we can efficiently find $D,\ b'$ such that:

$$f(x) \geq a^\top W_2 D z_1 + b' \Longleftarrow f(x) \geq a^\top W_2 z_2 + b \quad \forall x \in \mathcal{S}$$

[Z*W*CHD NeurIPS 2018]

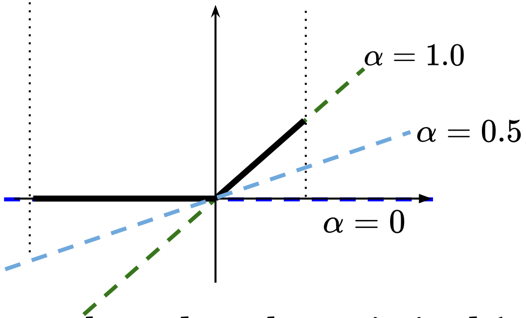
CROWN: propagating bounds through **non-linear** layers

Proof sketch: conservatively use linear bounds to replace a non-linear function.



Pre-activation bounds

(can be pre-computed using CROWN)



ReLU's lower bound can be optimized (**α**-CROWN)

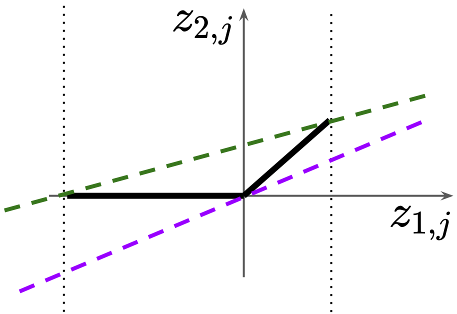
Theorem (informal): we can efficiently find $D,\ b'$ such that:

$$f(x) \geq a^\top W_2 D z_1 + b' \Longleftarrow f(x) \geq a^\top W_2 z_2 + b \quad \forall x \in \mathcal{S}$$

[**Z***W*CHD NeurIPS 2018]

CROWN: propagating bounds through **non-linear** layers

Proof sketch: conservatively use linear bounds to replace a non-linear function.



$$f(x) \geq a^\top W_2 z_2 + b$$

$$f(x) \geq \sum_j \left[(a^\top W_2)_j \cdot z_{2,j} \right] + b$$

$(a^\top W_2)_j \geq 0$ Choose lower bound

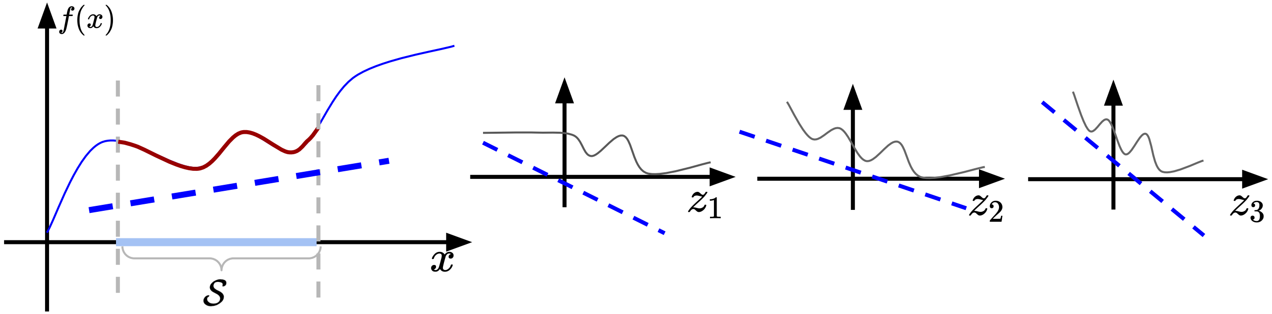
$(a^\top W_2)_j < 0$ Choose upper bound

Theorem (informal): we can efficiently find $D,\ b'$ such that:

$$f(x) \geq a^\top W_2 D z_1 + b' \Longleftarrow f(x) \geq a^\top W_2 z_2 + b \quad \forall x \in \mathcal{S}$$

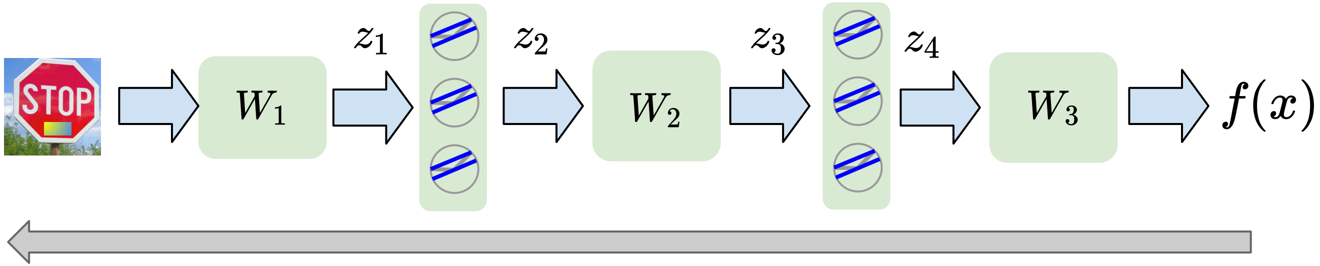
[**Z***W*CHD NeurIPS 2018]

CROWN: a linear bound propagation algorithm



Initial (in)equality:

$$f(x) = W_3 z_4$$

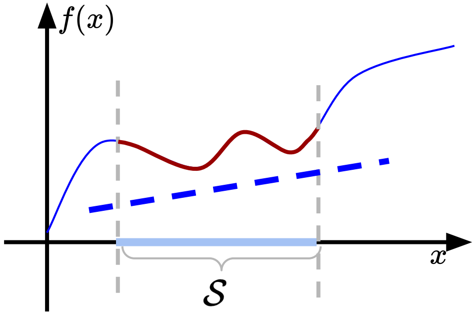


Always keep valid lower bounds

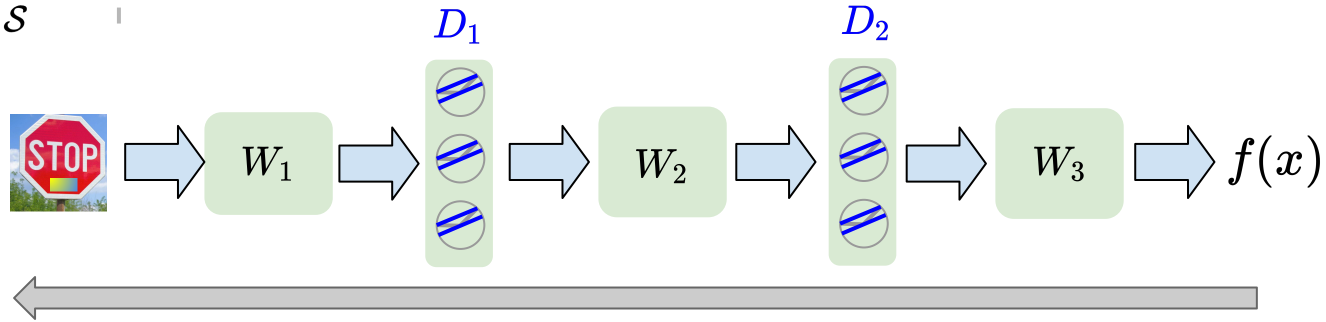
CROWN main theorem (simplified): $f(x) \geq a_{\text{CROWN}}^{\top} x + b_{\text{CROWN}} \quad \forall x \in \mathcal{S}$

[**Z***W*CHD NeurIPS 2018]

CROWN: a linear bound propagation algorithm



Bounds propagated through
simple matrix multiplations!
Fast and GPU-friendly



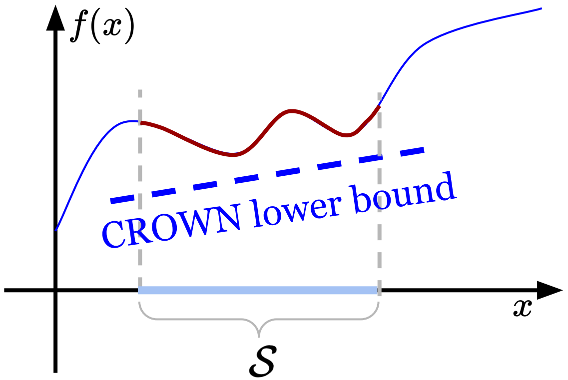
Always keep valid lower bounds

CROWN main theorem (simplified): $f(x) \geq a_{\text{CROWN}}^{\top} x + b_{\text{CROWN}} \quad \forall x \in \mathcal{S}$

$a_{\text{CROWN}} = W_3 D_2 W_2 D_1 W_1$

[Z*W*CHD NeurIPS 2018]

Prove the verification problem with CROWN



Prove: $\forall x \in \mathcal{S},\ f(x) > 0$

$x_1 \in \mathcal{S}$ $x_2 \in \mathcal{S}$ $x_3 \in \mathcal{S}$ …

Lower bound > 0 ⇨ $f(x) > 0$ ⇨ verified (always a stop sign)

`auto_LiRPA`: Verification Library for General Computation Graphs

Colab Demo:

http://PaperCode.cc/AutoLiRPA-Demo

The auto_LiRPA library on GitHub:

http://PaperCode.cc/AutoLiRPA

MILP/LP vs Bound Propagation

Bound propagation:

- Scalable and fast propagation
- GPU friendly
- Incomplete verification (will be extended in the next lecture)
- Bounds are looser compared to LP; much looser compared to MILP

MILP/LP:

- Tighter solution
- Does no scale (MILP ~10k neurons, LP ~100k neurons)
- Much slower; cannot utilize GPU