Verifying Quantized Neural Networks using SMT-Based Model Checking

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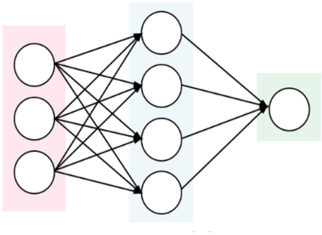
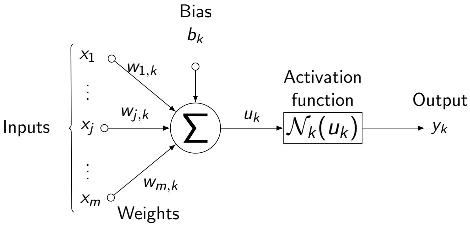
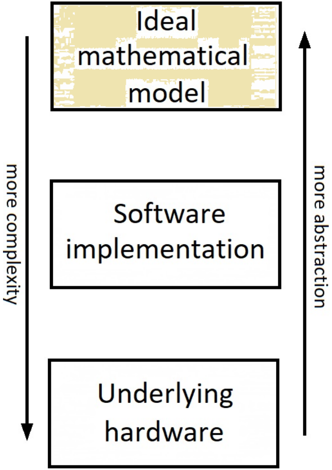
Neural networks: just mathematical functions?

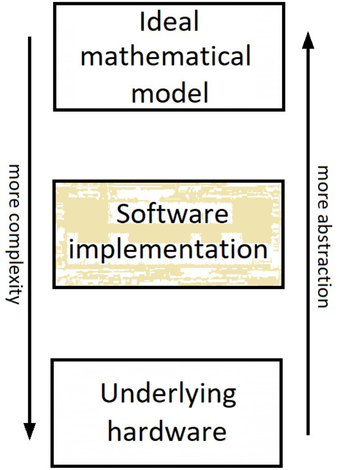






Neural networks: looking at the source code

```
float potential(float *w,
                unsigned int w_len,
                float *x,
                unsigned int x_len,
                float b) {

  if (w_len != x_len) {
    return 0;
  }

  float result = 0;

  for (unsigned int i = 0; i < w_len;
       ++i) {
    result += w[i] * x[i];
  }

  result += b;

  return result;
}
```



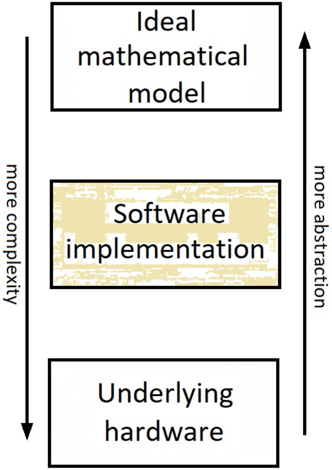
Research challenges

Verifying quantized NN

- Even floating-point is quantized!
- Fixed-point/integer arithmetics for low-power devices
- Approximated activation functions
- Complexity NP $\rightarrow$ PSPACE-hard

More software idiosyncrasies

- NaN, overflow, underflow
- Memory bugs, buffer overflows
- Concurrent execution bugs (GPUs)



Quantization effects

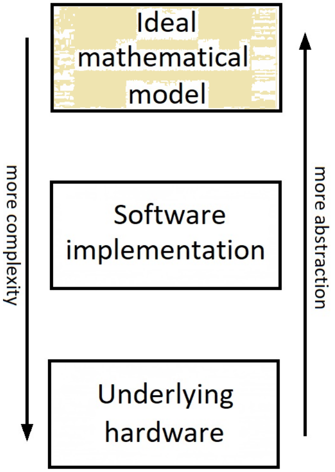
Safety Prop.		Number of bits													
		6	7	8	9	10	11	12	13		28	29	30	31	32
Set.	R_{40}	S	S	F	S	S	S	S	S	...	S	S	S	S	S
	R_{50}	S	S	F	F	F	F	F	F	...	F	F	F	F	S
Vers.	R_{20}	S	F	S	S	S	S	S	S	...	S	S	S	S	S
	R_{30}	S	F	S	S	S	S	S	S	...	S	S	S	S	S
	R_{40}	S	F	S	F	F	F	S	S	...	S	S	S	S	S
	R_{50}	S	F	F	F	F	F	F	F	...	F	F	F	F	F
Virg.	R_{20}	S	F	S	S	S	S	S	S	...	S	S	S	S	S
	R_{30}	S	F	S	S	S	S	S	S	...	S	S	S	S	S
	R_{40}	S	F	S	S	F	S	S	S	...	S	S	S	S	S
	R_{50}	S	F	F	F	F	F	F	F	...	F	F	F	F	F

Table: Effects of quantization on the safety of a NN for the Iris dataset.

Existing works

NN as an ideal mathematical function

- See last year's VNN-COMP'21
- Winner: $\alpha\beta$-CROWN
- Runners-up: VeriNet, Oval, ERAN...



Existing works

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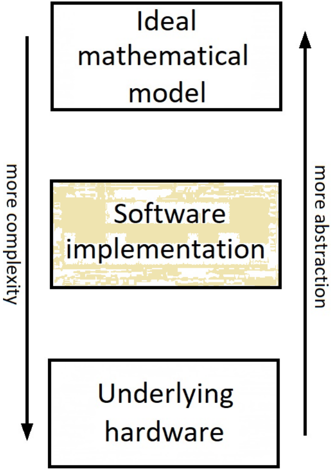
Quantization effects

- Giacobbe *et al.*, 2019 (ReLU-N)
- Henzinger *et al.*, 2021 (ReLU-N)
- Baranowski *et al.*, 2020 (fixed-point)

Other implementation effects

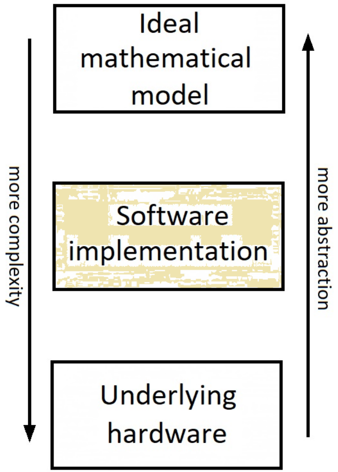
- Odena *et al.*, 2019 (fuzz testing)
- Sena *et al.*, 2019 (CUDA)



Our verification framework (high-level view)

Goal

- Support floating-point, fixed-point, integer and binary arithmetic
- Support all activation functions
- Let the user specify a wide range of safety properties



Our verification framework (high-level view)

Goal

- Support floating-point, fixed-point, integer and binary arithmetic
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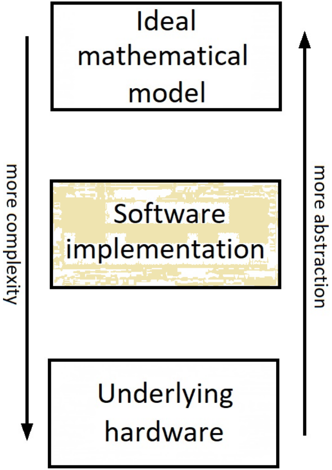
Main ideas

- Apply model checking techniques
- C code as a low level abstraction
- Safety property with `assume()` and `assert()` instructions
- Convert code + property into SMT
- Check satisfiability of SMT formula



Our verification framework (SMT encoding)

```c
int main() {
  _Bool x, y;
  int a, b, f;
  x = nondet_bool();
  y = nondet_bool();
  a = ((2*x) - (3*y));
  a = a < 0 ? 0 : a;
  b = (x + (4*y));
  b = b < 0 ? 0 : b;
  f = ((3*x) + y);
  f = f < 0 ? 0 : f;
  assert(a <= 2 && b <= 5 && f <= 4);
  return 0;
}
```

SSA

```
x1 == nondet_symbol(nondet0)
y1 == nondet_symbol(nondet1)
a1 == 2 * (int)x1 - 3 * (int)y1
a2 == (a1 < 0 ? 0 : a1)
b1 == (int)x1 + 4 * (int)y1
b2 == (b1 < 0 ? 0 : b1)
f1 == 3 * (int)x1 + (int)y1
f2 == (f1 < 0 ? 0 : f1)
(assert) a2 <= 2
(assert) b2 <= 5
(assert) f2 <= 4
```

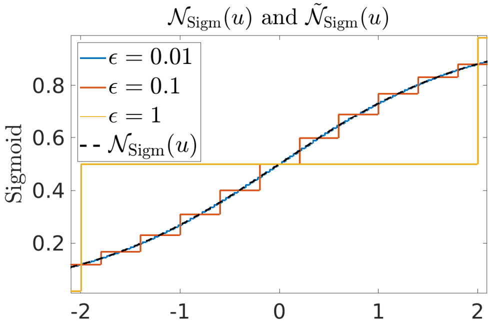
aggressive simplifications

```
x1 == nondet_symbol(nondet0)
y1 == nondet_symbol(nondet1)
a1 == 2 * (int)x1 - 3 * (int)y1
a2 == (a1 < 0 ? 0 : a1)
```

SMT

```
...
(assert(= a1 (- (* 2 x1) (* 3 y1))))
(assert (and (< a1 0) (= a2 0)))
(assert (and (> a1 0) (= a2 a1)))
...
```

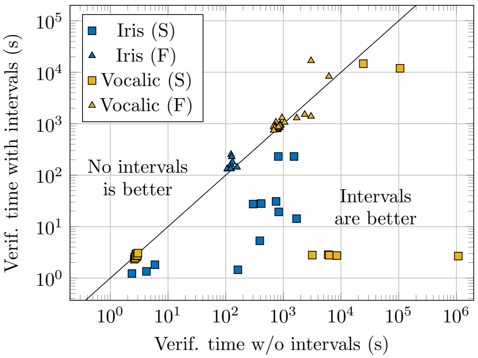
Our verification framework (activation functions)



Encoding non-linear functions

- Piecewise linear (e.g. ReLU) $\rightarrow$ if-then-else
- Others (e.g. sigmoid, tanh) $\rightarrow$ lookup table (DSP-style)
- Speeds up both inference and verification!

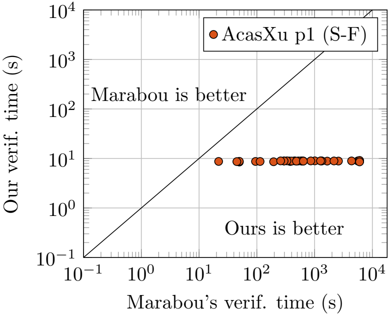
Our verification framework (interval analysis)

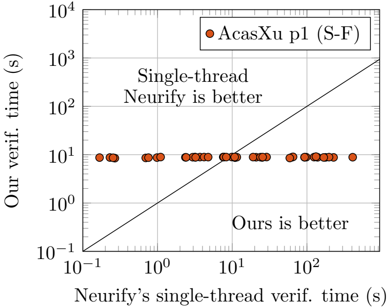


Input set propagation

- Transferable from verification of ideal NNs
- Generates an overapproximation of the neuron values
- Reduces the search space for safe (S) instances

Our verification framework (comparison with SOTA)





Warning: this is not an equal contest!

- Comparison between infinite precision and fixed-point
- Useful as a qualitative result

Conclusions

Summary

- Implementations of NNs are software!
- Quantization effects, finite arithmetic, other potential bugs
- Higher theoretical complexity than verifying ideal NNs
- Positive note: similar verification time in practice

Further resources

- Try our QNNVerifier tool:
- `https://arxiv.org/abs/2111.13110`
- Read our pre-print journal paper:
- `https://arxiv.org/abs/2106.05997JournalPaper`

Thank you!