Towards Cognitive AI Systems: A Survey and Prospective on Neuro-Symbolic AI

CoCoSys — CENTER FOR THE CO-DESIGN OF COGNITIVE SYSTEMS

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CURRENT AI SYSTEMS

❖ **Current AI Systems**

✓ Features:
- Deep neural network
- Extensive dataset
- Large computing power

✓ Challenges:
- Unsustainability
- Lack robustness/explainability
- Limited human-AI collaboration

❖ **This work:**

✓ Algorithm: Systematic review of recent neuro-symbolic AI algorithms

✓ Hardware: Characterize performance and computational operators of neuro-symbolic AI
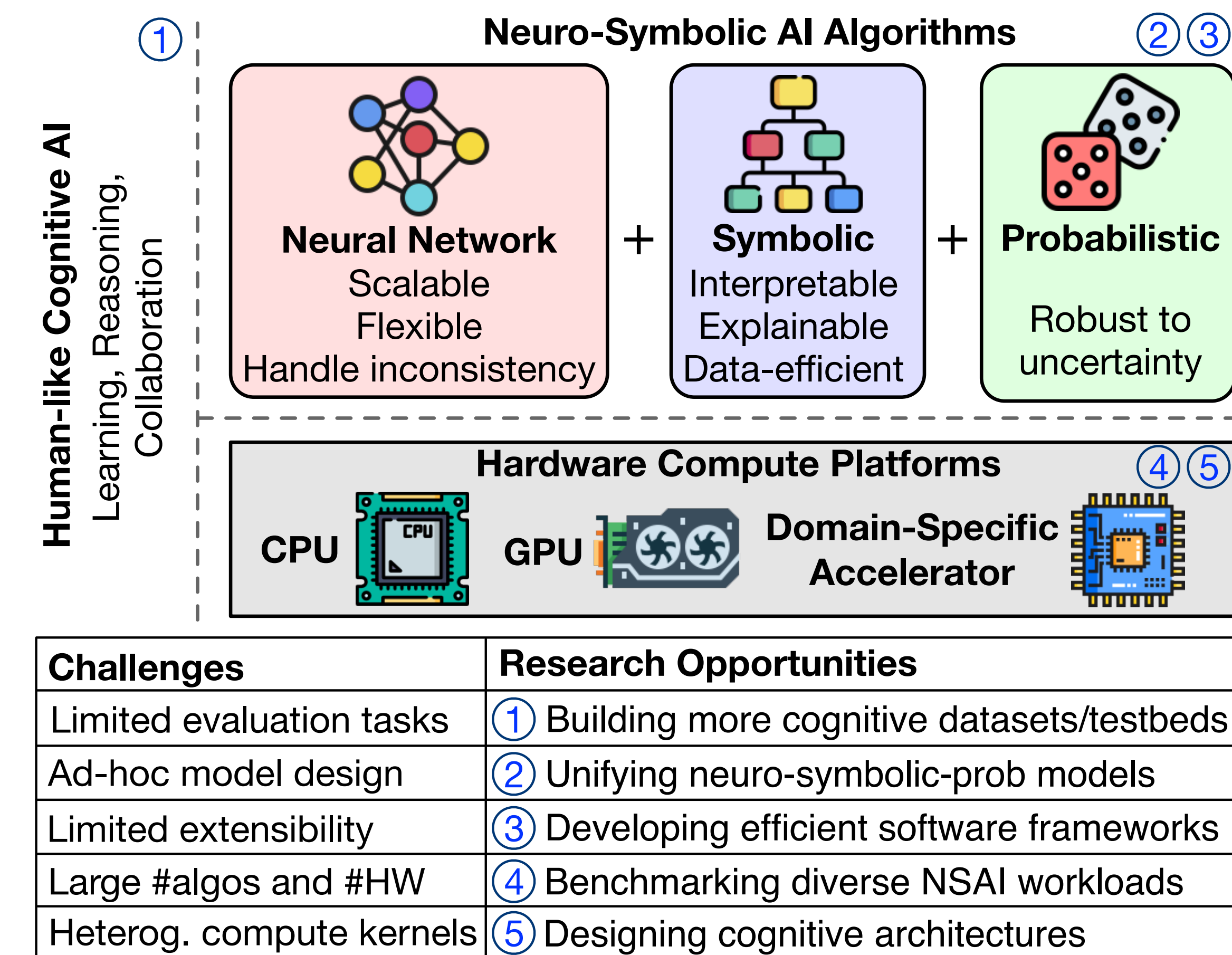
NEURO-SYMBOLIC AI SYSTEMS

❖ **An Emerging AI Paradigm: Neuro-Symbolic AI**

✓ Features: neuro + symbolic + probabilistic
- Neuro: scalable, flexible, handle inconsistency
- Symbolic: interpretable, explainable
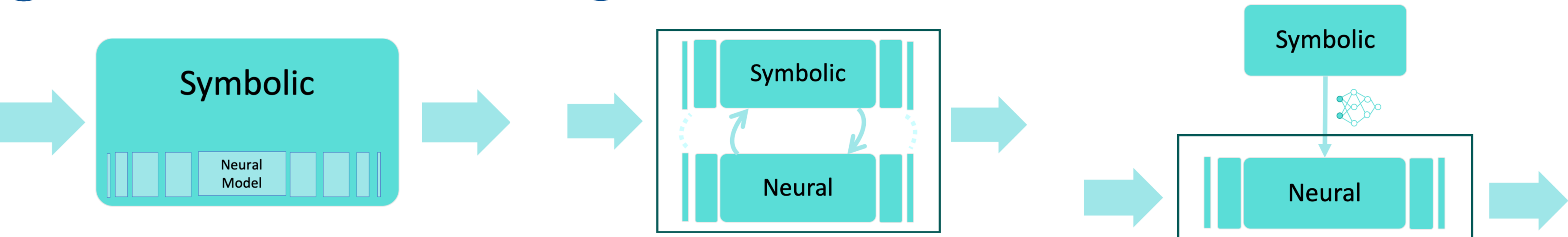- Probabilistic: robust to uncertainty

✓ Advantages:
- Improve efficiency, robustness, explainability
- Human-like reasoning capabilities
- Collaborative human-AI applications

Neuro-Symbolic AI Algorithms: Neural Network (Scalable, Flexible, Handle inconsistency) + Symbolic (Interpretable, Explainable, Data-efficient) + Probabilistic (Robust to uncertainty)

Hardware Compute Platforms: CPU, GPU, Domain-Specific Accelerator

Challenges	Research Opportunities
Limited evaluation tasks	① Building more cognitive datasets/testbeds
Ad-hoc model design	② Unifying neuro-symbolic-prob models
Limited extensibility	③ Developing efficient software frameworks
Large #algos and #HW	④ Benchmarking diverse NSAI workloads
Heterog. compute kernels	⑤ Designing cognitive architectures

NEURO-SYMBOLIC AI CATEGORIES

❖ **Criterion:** how neuro-symbolic integrated into a cohesive system

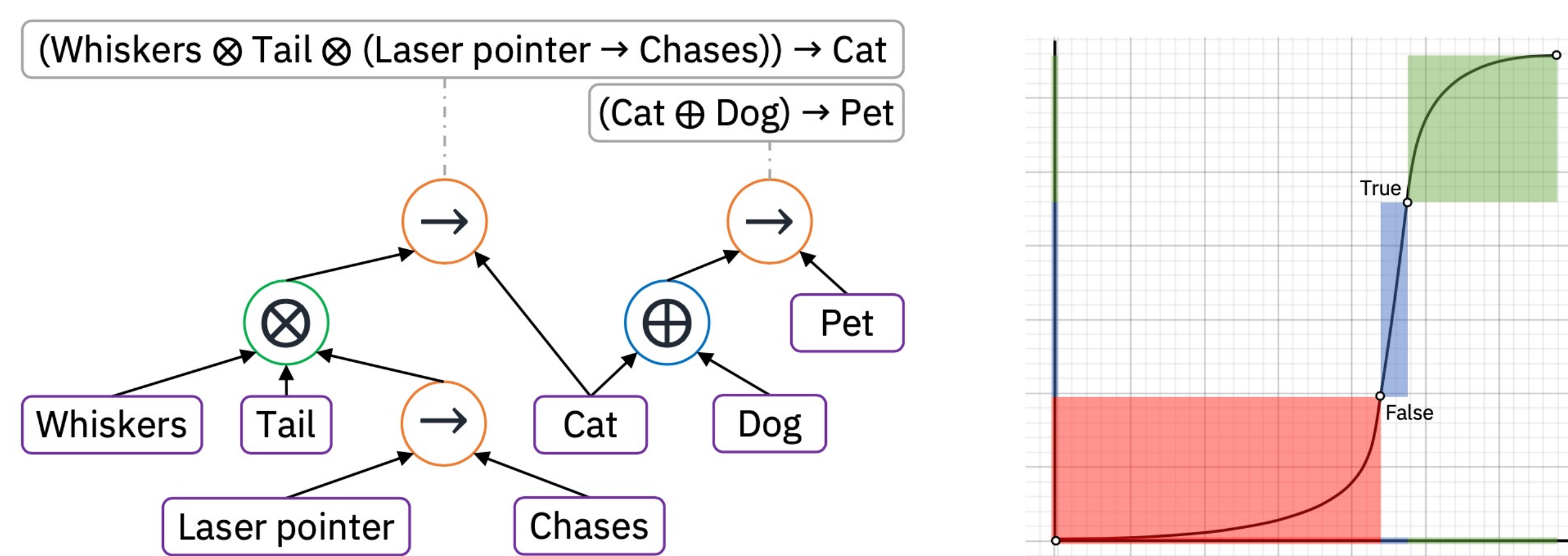① Symbolic[Neuro]
② Neuro|Symbolic
③ Neuro:Symbolic->Neuro
④ Neuro_Symbolic
⑤ Neuro[Symbolic]

✓ Representative Underlying Operations

Underlying Operations	Examples
Fuzzy logic (LTN)	$F = \forall x (isCarnivor(s)) \rightarrow (isMammal(x))$ $\{isCarnivor(s):[0,1], isMammal(x):[1,0]\} \rightarrow F = [1,0]$
Mul and Add (NVSA)	$X_i \in \{+1, -1\}^d \rightarrow (X_i \cdot X_j)/(X_i + X_j)$
Pre-defined objects (NSVQA)	equal_color: $(entry, entry) \rightarrow Boolean$ equal_integer: $(number, number) \rightarrow Boolean$

NEURO-SYMBOLIC AI ALGORITHMS

| Category	NSAI Algorithm	Underlying Operation	If Vector
Symbolic[Neuro]	AlphaGo (Silver et al., 2017)	NN, MCTS	Vector
Neuro|Symbolic	NVSA (Hersche et al., 2023)	NN, mul, add	Vector
	NeuPSL (Pryor et al., 2022)	NN, fuzzy logic	Vector
	NSCL (Mao et al., 2019)	NN, add, mul, div, log	Vector
	NeurASP (Yang et al., 2020)	NN, logic rules	Non-Vector
	ABL (Dai et al., 2019)	NN, logic rules	Non-Vector
	NSVQA (Yi et al., 2018)	NN, pre-defined objects	Non-Vector
Neuro:Symbolic →Neuro	LNN (Riegel et al., 2020)	NN, fuzzy logic	Vector
	Symbolic Mathematics (Lample & Charton, 2019)	NN	Vector
	Differentiable ILP (Evans & Grefenstette, 2018)	NN, fuzzy logic	Vector
Neuro_Symbolic	LTN (Badreddine et al., 2022)	NN, fuzzy logic	Vector
	Deep ontology networks (Hohenecker & Lukas, 2020)	NN	Vector
Neuro[Symbolic]	GNN+attention (Lamb et al., 2020)	NN, SpMM, SDDMM	Vector
	NLM (Dong et al., 2019)	NN, permutation	Vector

NEURO-SYMBOLIC AI SYSTEM PROFILING

❖ **Selected Neuro-Symbolic AI Models**

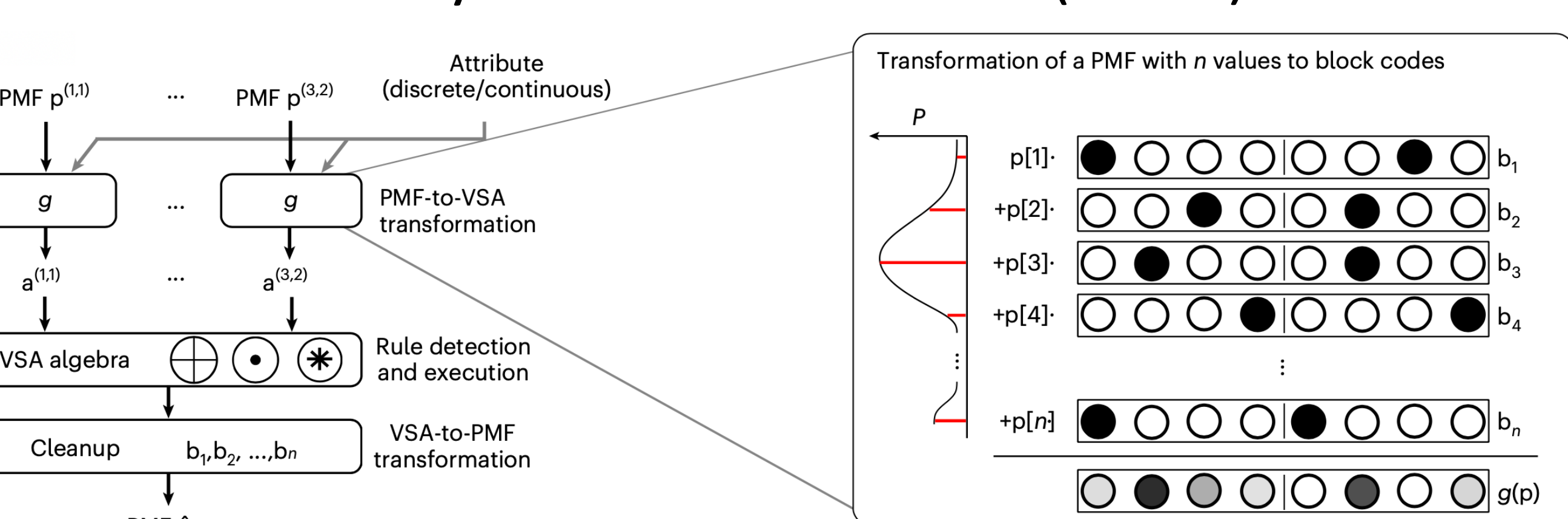✓ Logical Neural Network (LNN)

✓ Logical Tensor Network (LTN)
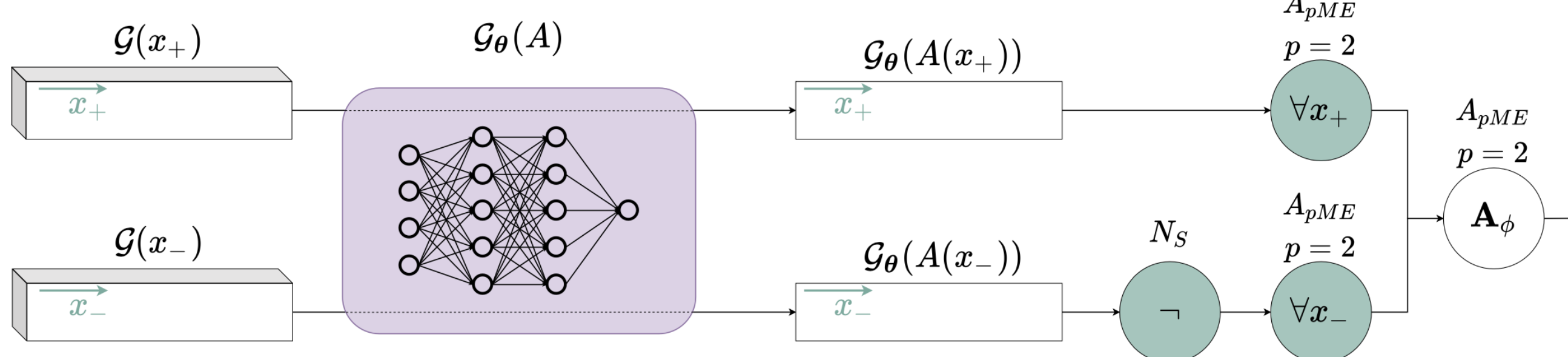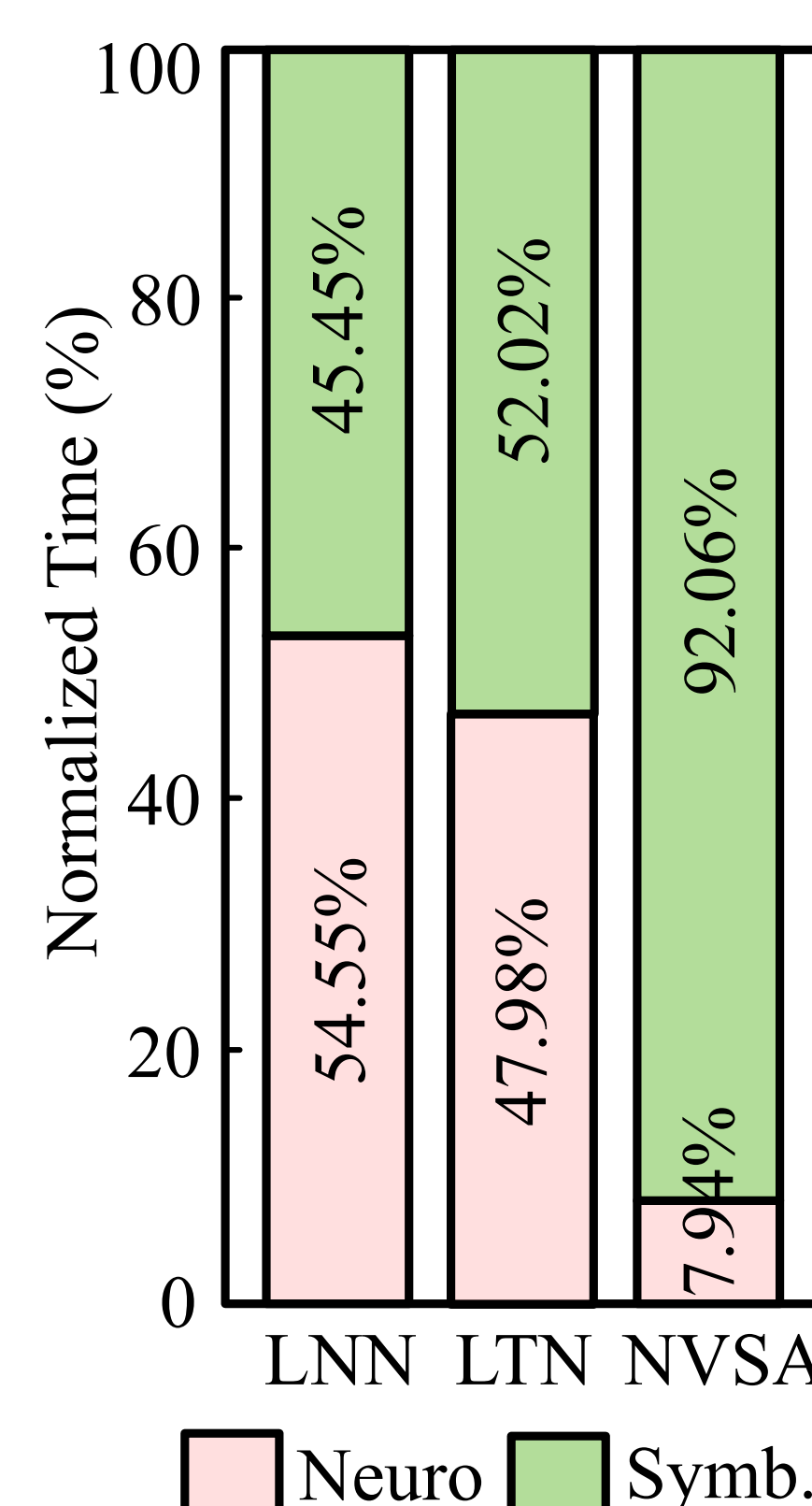

✓ Neuro-Vector-symbolic Architecture (NVSA)

❖ **Runtime Analysis**

✓ Methodology: PyTorch Profiler

✓ Hardware: Intel Xeon 4114 CPU, Nvidia RTX 2080 Ti GPU

❖ **Observations:**

✓ Symbolic workloads are not negligible and may become system bottleneck.

✓ Symbolic workloads in critical path.

✓ Potential scalability issue (e.g., in NVSA, test case size 2x2 -> 3x3, total runtime increases 5.02x)

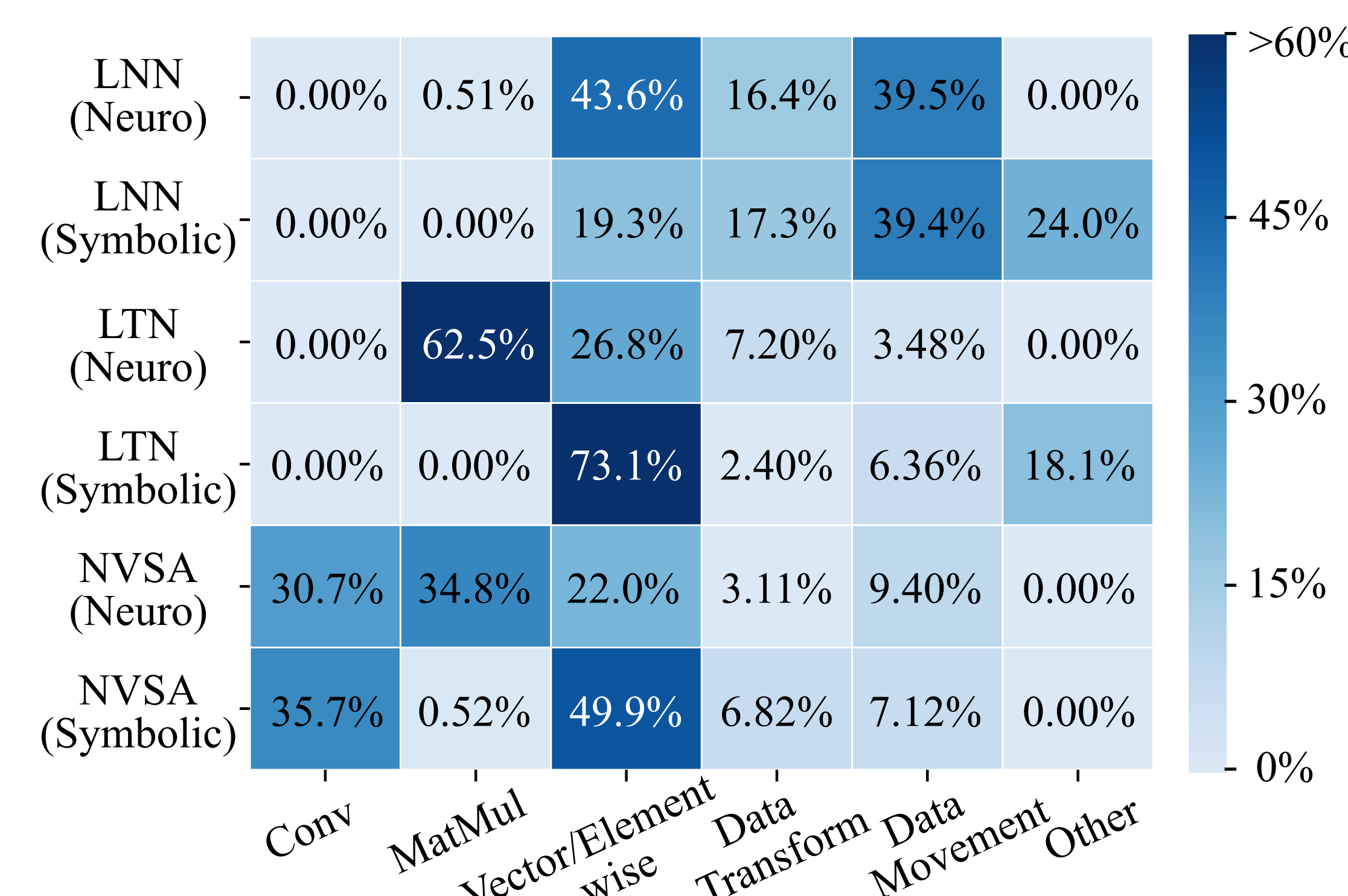❖ **Workload Analysis**

✓ Methodology: six operator categories

❖ **Observations:**

✓ Neuro workload is dominated by MatMul and vector/element-wise operations.

✓ Symbolic workload is dominated by vector/element-wise, logic operations.

✓ Data movement, complex control flow, low operational intensity.