OCTAL: Graph Representation Learning for LTL Model Checking

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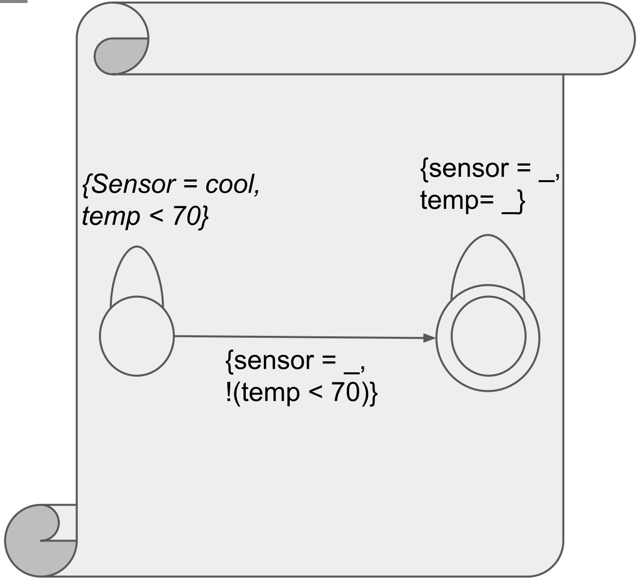
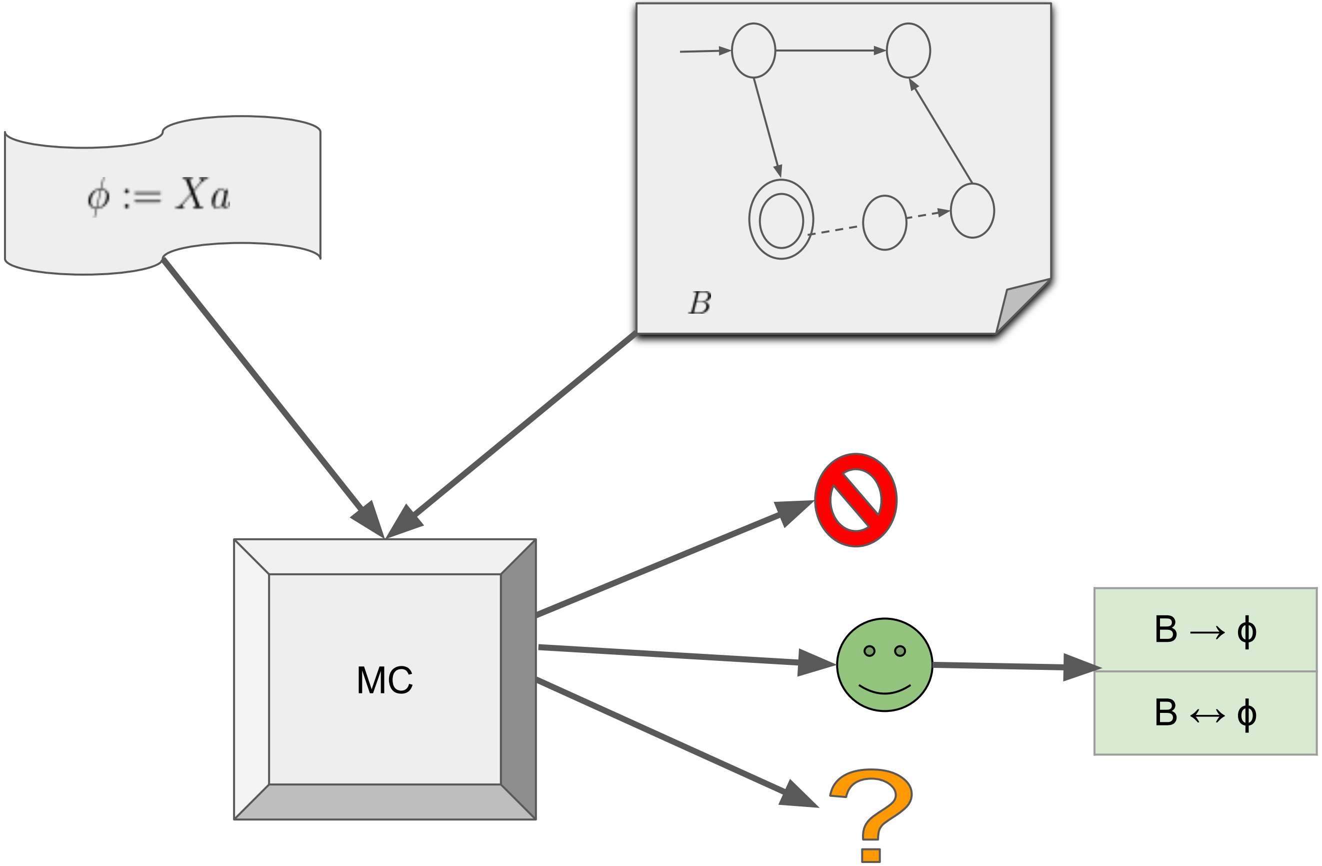
(Sensor = cool) until
(temperature >= 70)

?



Model Checking



LTL Model Checking - Specification

- Specification is expressed using Linear Temporal Logic

Symbol	G	F	R	W	M	X	U
Meaning	globally	finally	release	weak until	strong release	next	until

- a U b - *a is true “until” b is true*

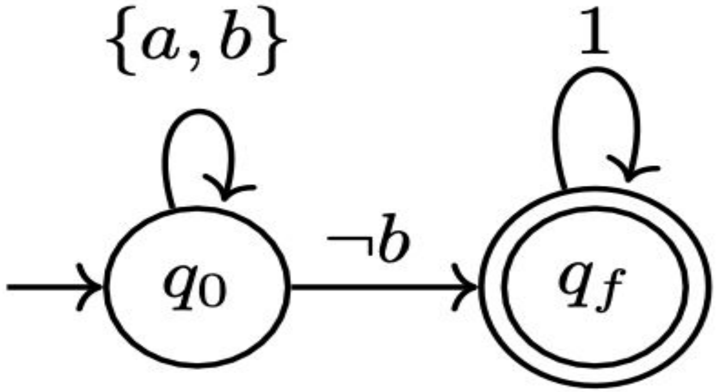
  {aaaab…,ba….,aacb…,abb….}

- Ga - *a is “always” true*

  {aaaaa…,{a,b}a….,aacb…,abb….}

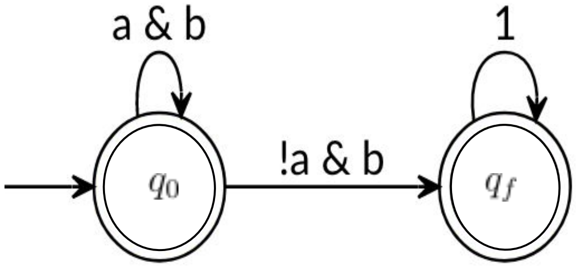
LTL Model Checking - System (Model)

- System is expressed using a Büchi Automaton

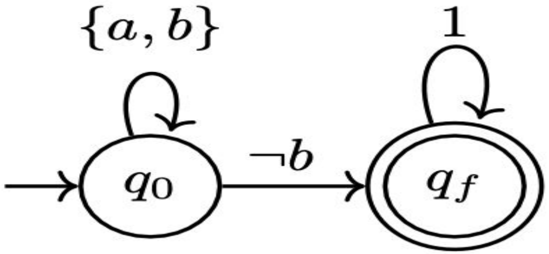


(a) B accepting $(a\,U\,!b)$.

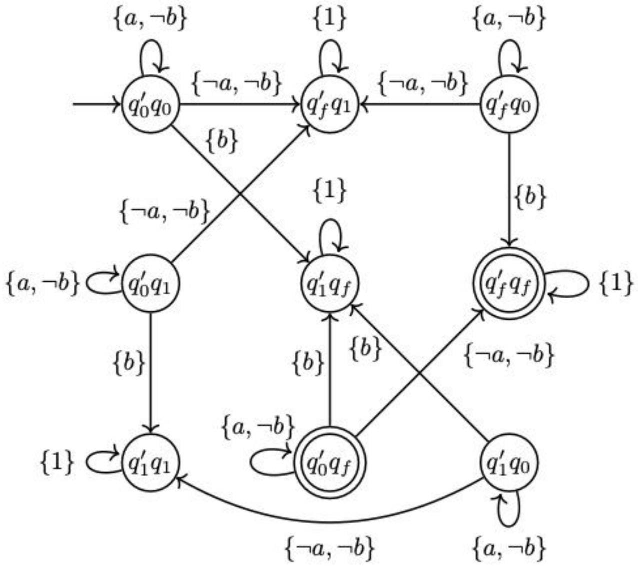
Traditional Model Checking



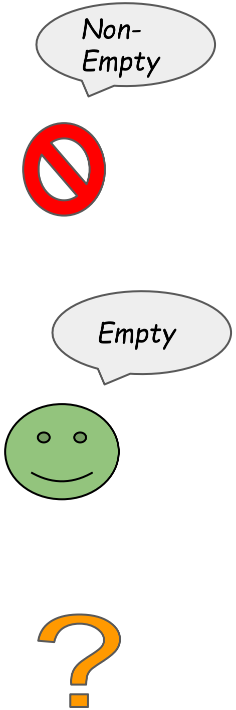
$B_{\neg\phi}$ accepting !(a U !b)



B accepting (a U !b).

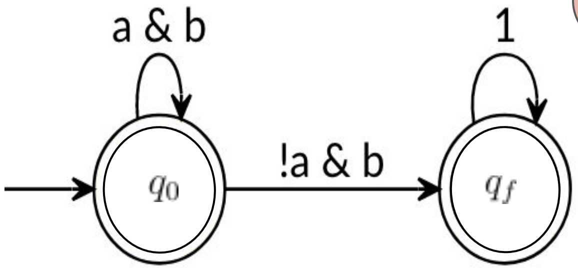


$B' = B \times B_{\neg\phi}$

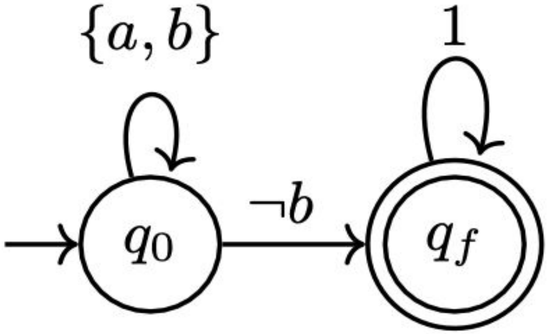


Challenges of Traditional Model Checking

2^|ϕ|

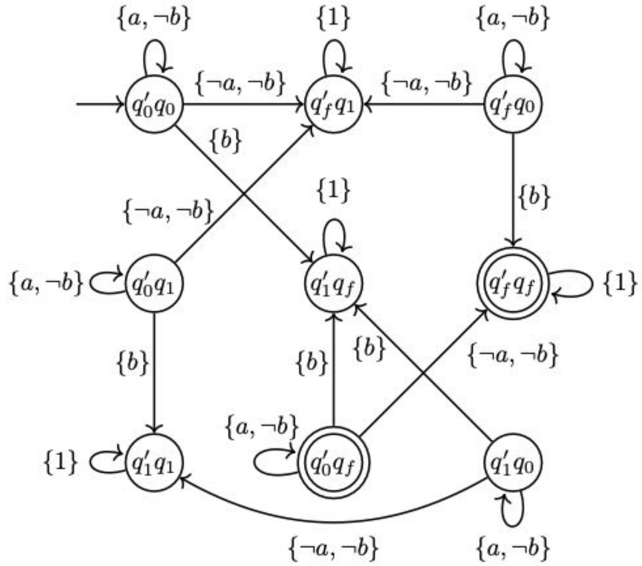


$B_{\neg\phi}$ accepting !(a U !b)



B accepting $(a\, U\, !b)$.

|B| × 2^|ϕ|



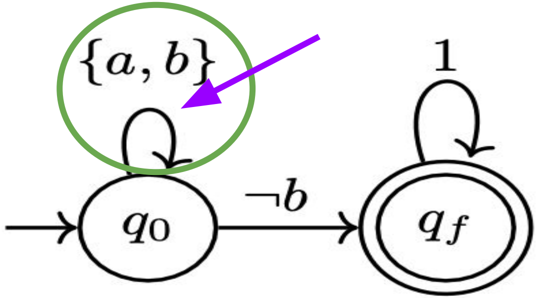
$B' = B \times B_{\neg\phi}$

Exponential time and space

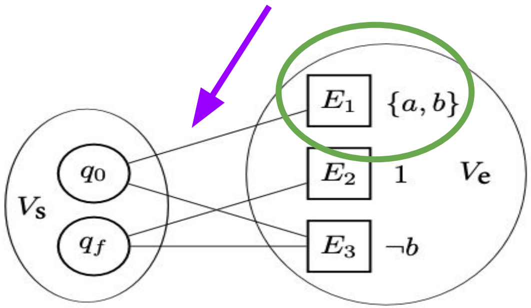
OCTAL: Graph Representation Learning for LTL Model Checking

- First Graph Representation Learning-based framework for LTL Model Checking
- Takes advantage of inherent graph structures of automaton and specification to learn embeddings of states and transitions
- Aims to decrease the high cost of model checking

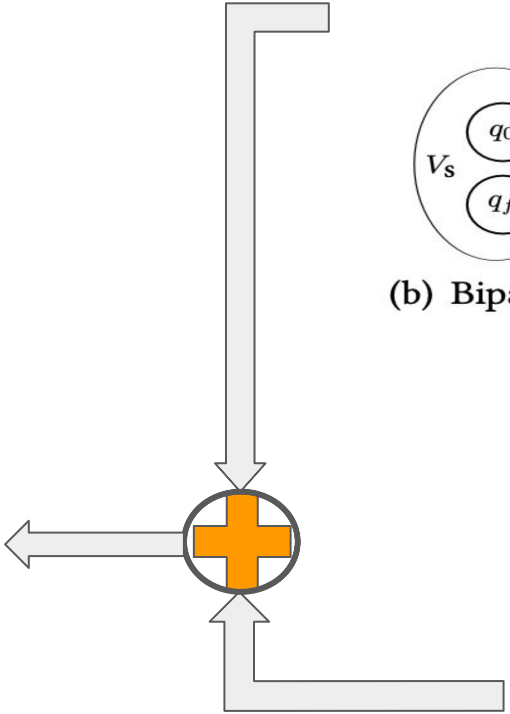
Formulate Model Checking as Graph Representation Learning

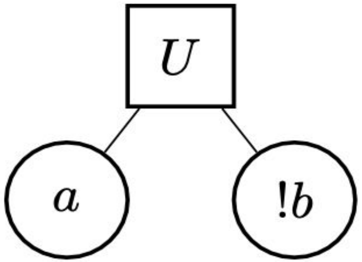


(a) B accepting $(a\ U\ !b)$.

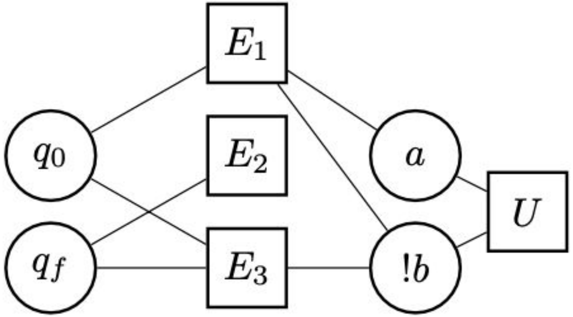


(b) Bipartite graph $\mathcal{G}$ of B.



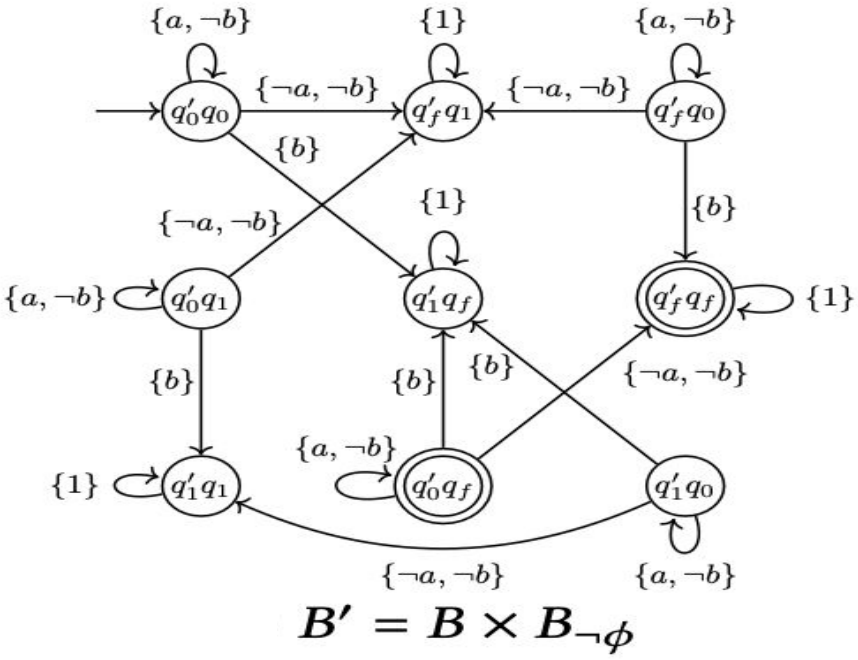


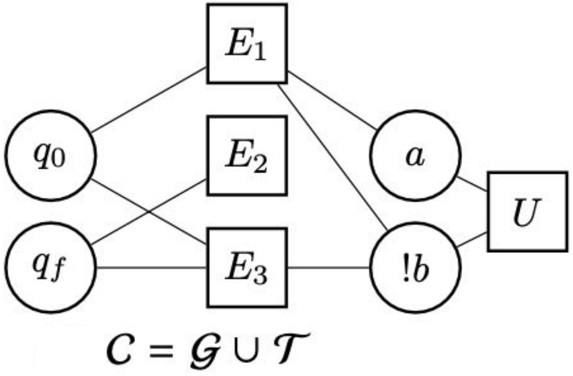
(c) Expression Tree $\mathcal{T}$ of ϕ : $(a\ U\ !b)$.



(d) $C = \mathcal{G} \cup \mathcal{T}$

Complexity Comparison

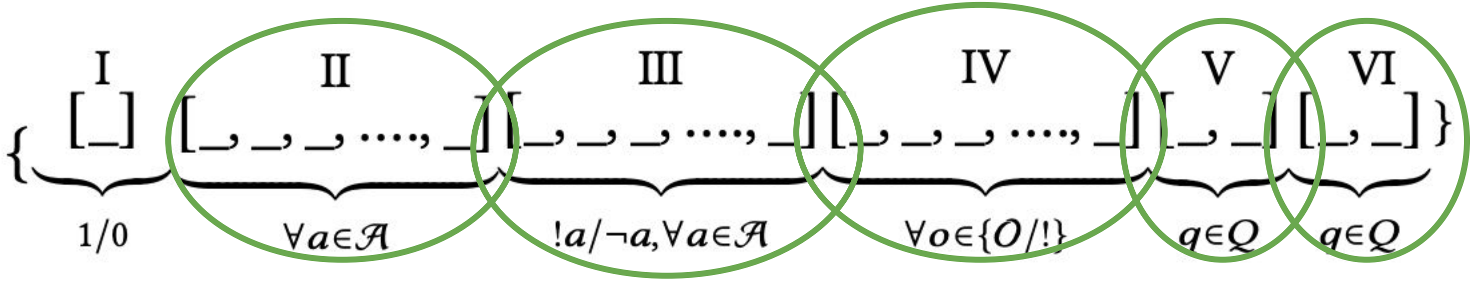




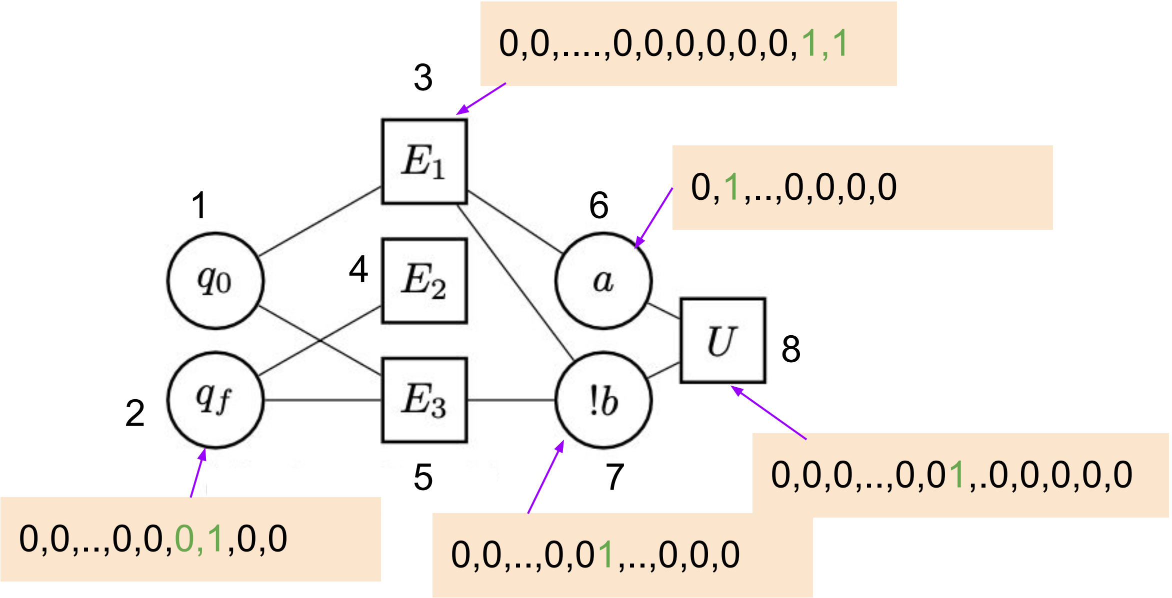
Traditional MC: |B| × 2^|ϕ|

OCTAL: |B + ϕ|

OCTAL: Node Encoding



Initial	Final
0	0
0	1
1	0
1	1



Model Checking Scenarios

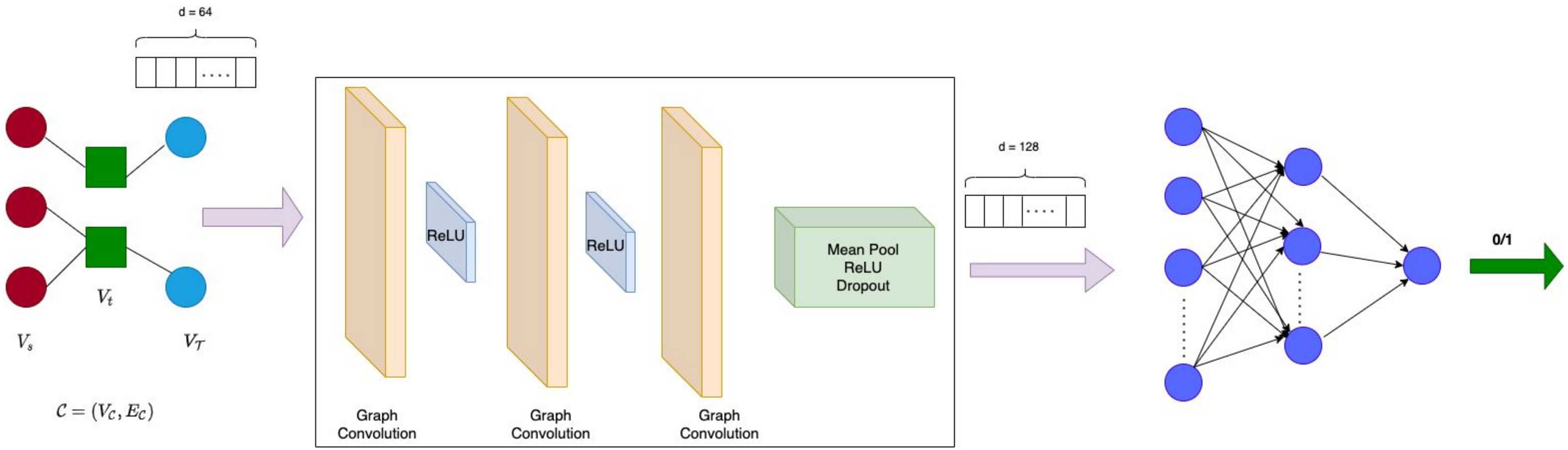
General	Special (Equivalence)
$B \leftrightarrow \phi$	$B \leftrightarrow \phi$
$B \rightarrow \phi$	$B \rightarrow \phi$
$B \leftarrow \phi$	$B \leftarrow \phi$
$B \neq \phi$	$B \neq \phi$

Datasets

Dataset	Len_LTL	#State	#Transition
Synth	[1 - 80]	[1 - 95]	[1 - 1,711]
RERS	[3 - 39]	[1 - 21]	[3 - 157]

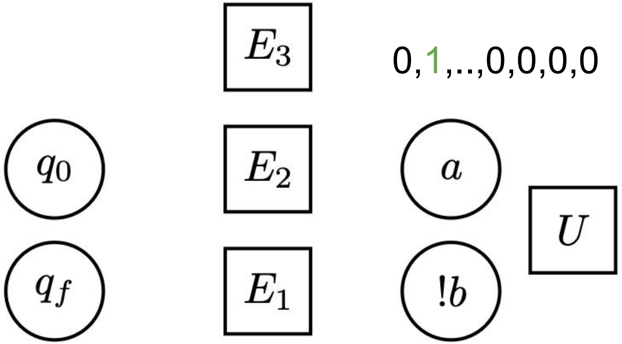
- Synth is a synthetic dataset to test the effectiveness of OCTAL on diverse and complex systems (specifications)
- RERS is a dataset adapted from the LTL specifications of RERS'19
- RERS is designed to test the effectiveness of OCTAL on real world, traditional MC oriented systems (specifications)
- Synth and RERS are designed for both general and special model checking cases
- The datasets comprise of tuples of the form (B, ϕ, ***l***)

Architecture and Experimental Setup

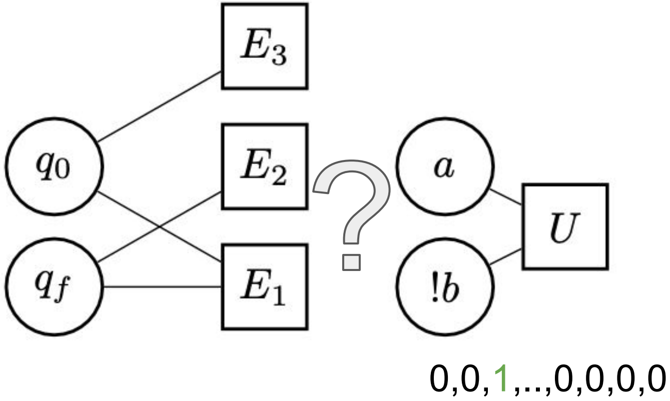


- Trained and validated with an 80-20 split
- All sets are randomly shuffled and contain equal number of positives and negatives
- Three baselines are considered for performance analysis

Baseline Models



MLP



Link Predictor

Evaluation Results - General Scenario

Models	Accuracy		Precision		Recall	
	SynthGen	RERSGen	SynthGen	RERSGen	SynthGen	RERSGen
MLP	46.44±0.86	51.73±1.38	46.83±0.64	51.72±1.46	52.19±3.66	48.01±9.36
LinkPredictor	60.76±0.81	67.93±1.18	61.86±0.92	66.66±1.39	56.12±0.81	71.83±1.17
OCTAL(GCN)	76.76±0.95	88.23±0.75	84.77±1.20	88.97±1.11	65.26±2.27	87.32±2.21
OCTAL(GIN)	**77.96±1.71**	**89.48±0.61**	**85.37±1.11**	**89.63±2.17**	**67.51±3.99**	**89.37±1.73**

Dataset	**LTL3BA(I)**	**LTL3BA(O)**	**Spot(I)**	**Spot(O)**
SynthGen	351×	11×	52×	1.7×
RERSGen	54×	2×	30.5×	1.6×

→ SOTA MCs

I := inference
O := graph + I

Evaluation Results - Special Scenario

Models	Accuracy		Precision		Recall	
	SynthSpec	RERSSpec	SynthSpec	RERSSpec	SynthSpec	RERSSpec
MLP	48.90±0.80	59.53±1.66	48.90±0.75	59.07±1.10	45.39±2.86	61.96±5.67
LinkPredictor	73.13±1.11	73.54±1.98	72.39±0.98	70.02±1.98	74.87±2.80	82.41±2.84
OCTAL(GCN)	95.18±0.47	95.45±0.72	**95.32±0.71**	91.82±1.02	95.03±0.76	**99.81±0.29**
OCTAL(GIN)	**95.37±0.69**	**96.19±0.62**	94.57±1.39	**95.52±0.69**	**96.30±0.68**	96.94±1.91

Dataset	**LTL3BA(I)**	**LTL3BA(O)**	**Spot(I)**	**Spot(O)**
SynthSpec	282×	9.3×	49×	1.6×
RERSSpec	37.3×	2×	30.5×	1.6×

SOTA MCs

I := inference
O := graph + I

Conclusions and Future Work

- OCTAL is the first GRL-based framework for LTL model checking
- OCTAL achieves significant speedups over SOTA tools with consistent prediction performance
- OCTAL consistently achieves ~95% accuracy on special model checking
- OCTAL can be used to make MC affordable
- In future, we propose to extend OCTAL to support counter example traces for the “no” predictions.

Code

paper