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Symbolic Verification of Message Passing Interface Programs

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High Performance Computing

MPI Paradigm

- Key features of MPI Applications
  - Non-deterministic, e.g. wildcard receive
  - Blocking and non-blocking communications
  - Data and control intensive
- MPI programs are hard to develop and maintain

Verifying MPI programs is challenging

Challenges

- Non-determinism (Soundness)
  - Input && Schedule coverage

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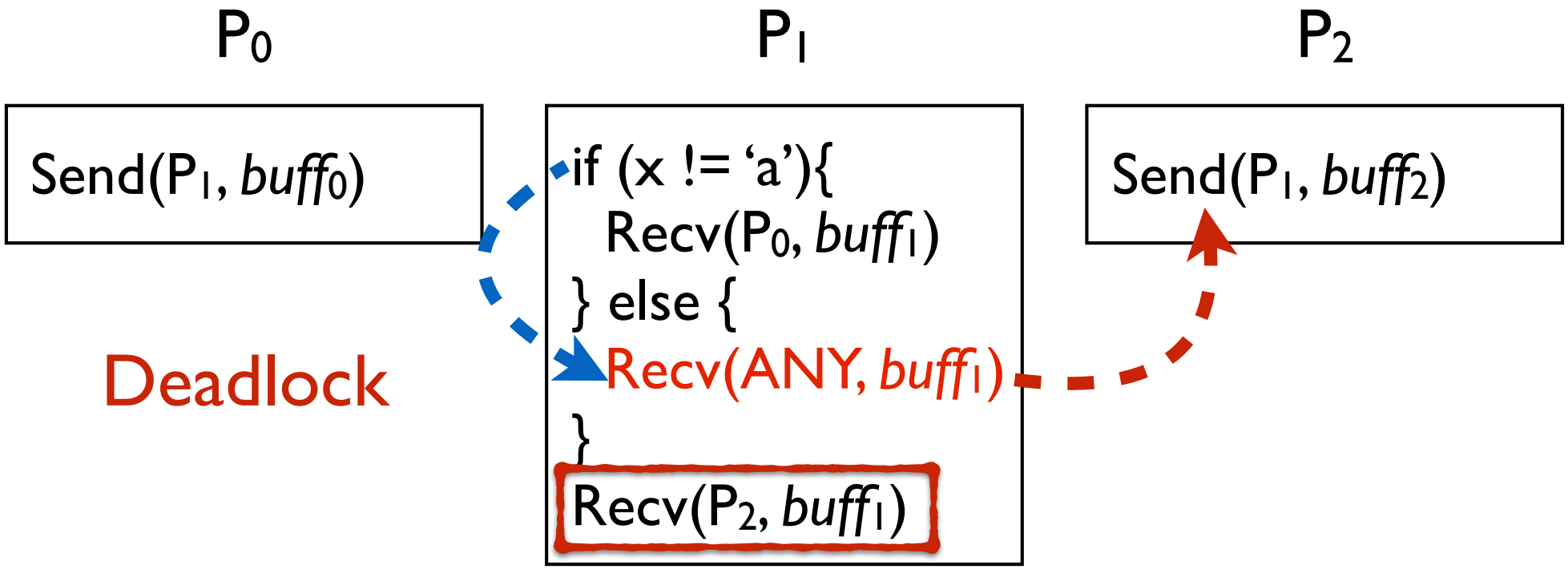


Existing Work of MPI Verification

	Automation	Input Coverage	Non-Blocking
CIVL(TASS)	Yes	Yes	No
MOPPER	Yes	No	Yes
MPI-SPIN	No	Yes	Yes

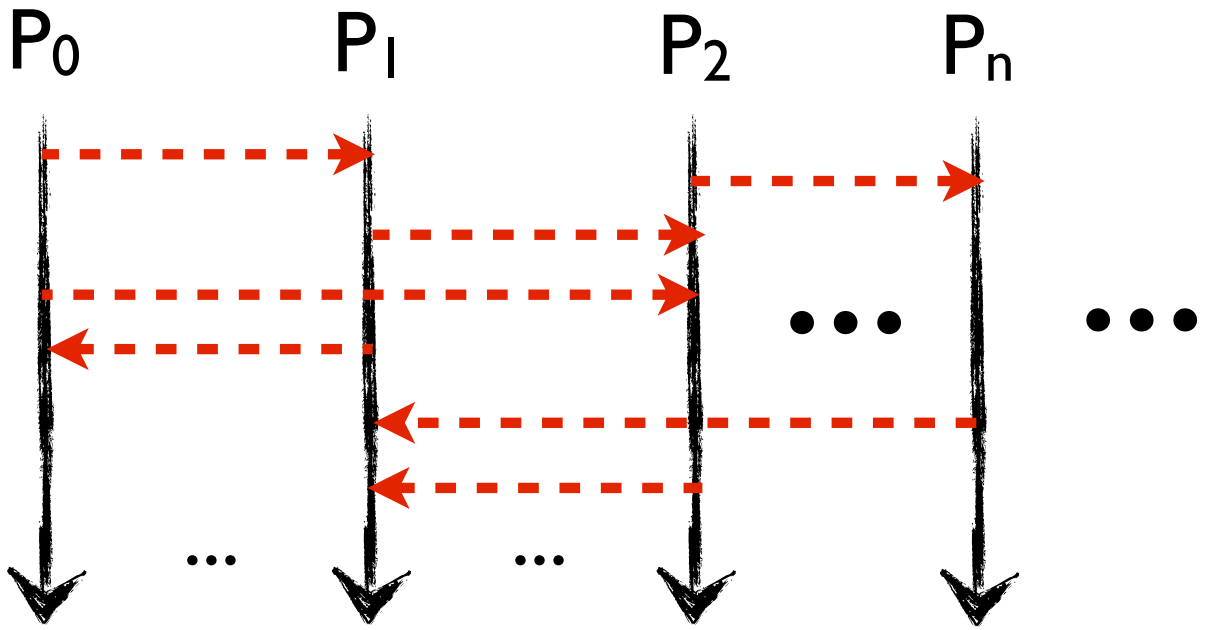
Either do not support input-related verification or fail to support the verification of non-blocking MPI programs

Existing Work of MPI Verification

	Automation	Input Coverage	Non-Blocking
CIVL(TASS)	Yes	Yes	No
MOPPER	Yes	No	Yes
MPI-SPIN	No	Yes	Yes
MPI-SV	**Yes**	**Yes**	**Yes**

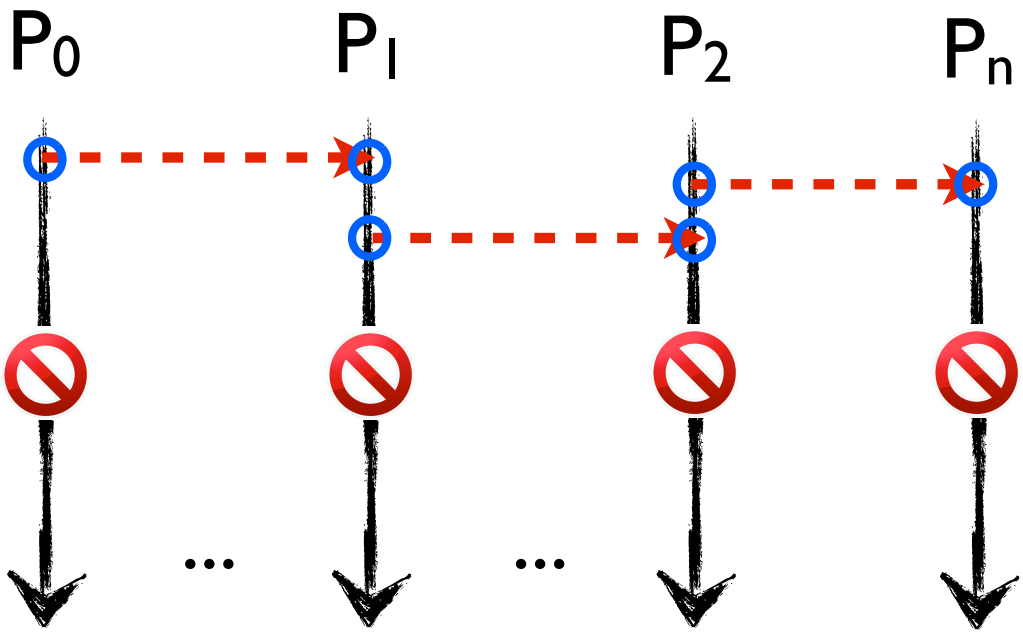
Challenges

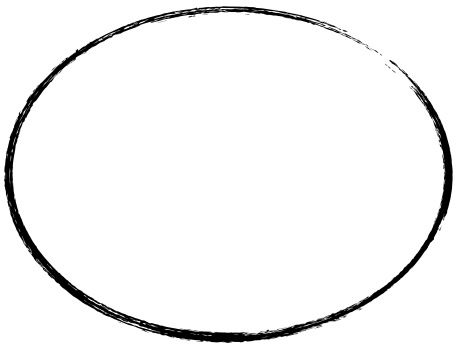
- The explosion of state space
  - Parallel execution, wildcard receive, branches
  - Exponential increasing



Key Ideas (1/2)

- Challenge 1: non-determinism
  - Symbolic execution for input coverage
  - Blocking-driven matching of wildcard receives

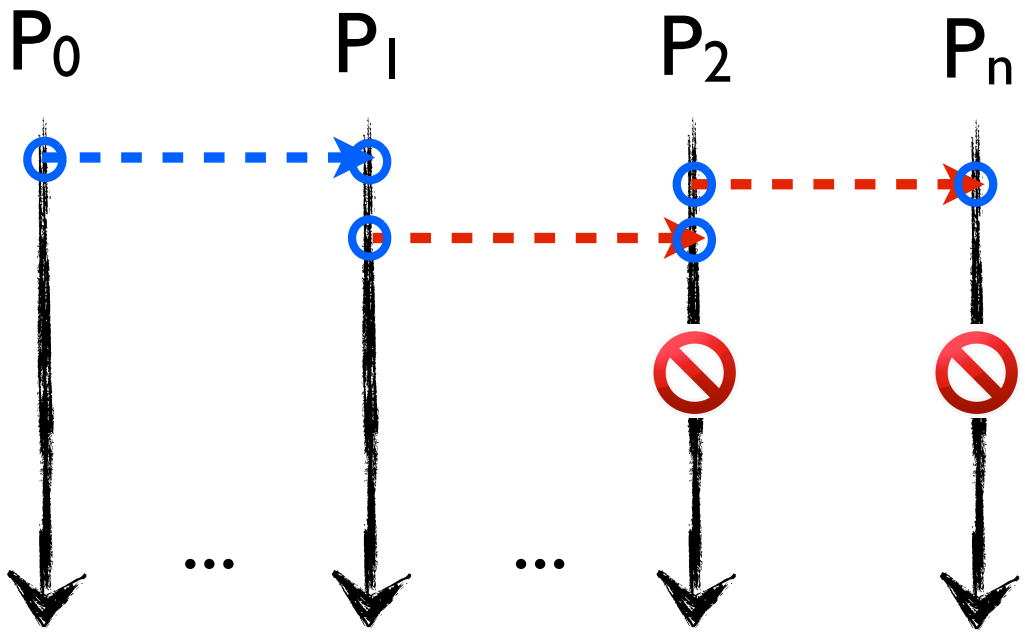




Message Matchings

Key Ideas (1/2)

- Challenge 1: non-determinism
  - Symbolic execution for input coverage
  - Blocking-driven matching of wildcard receives

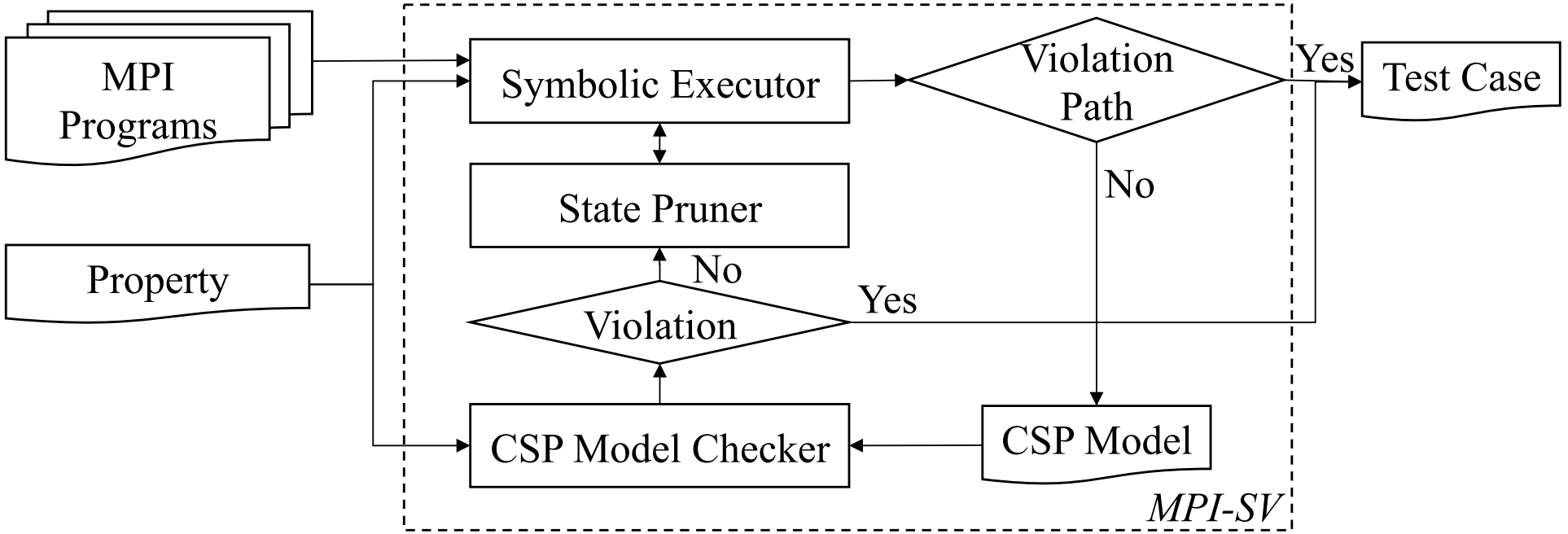


The happens-before requirements in MPI standard are preserved

Key Ideas (2/2)

- Challenge 2: the explosion of state space
  - Partial order reduction
  - Model checking-based boosting

Basic Framework



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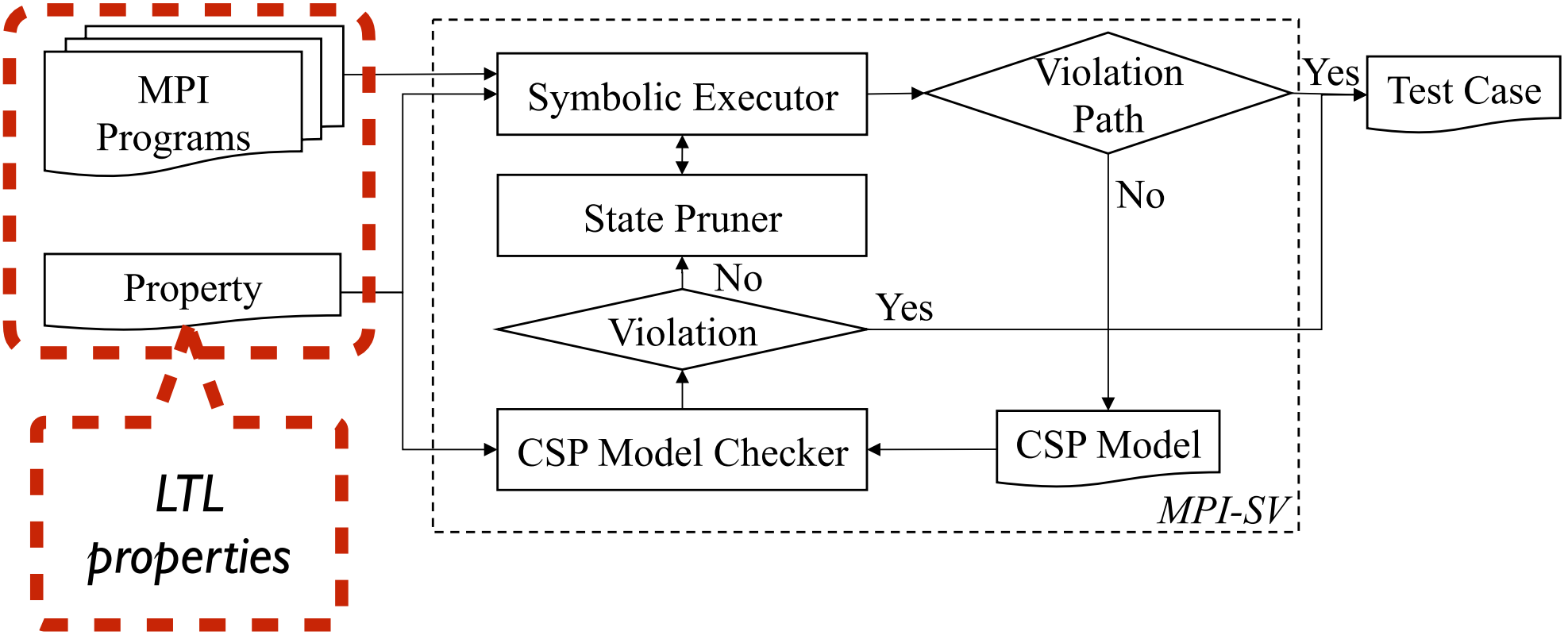

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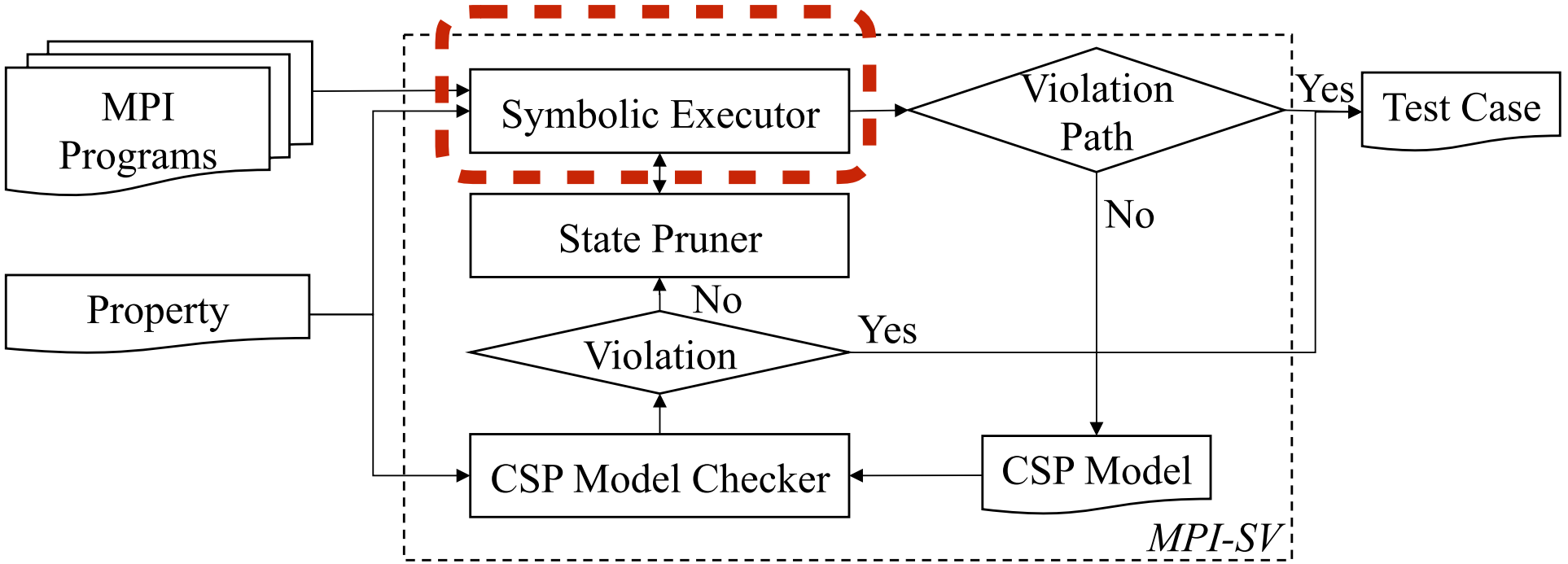

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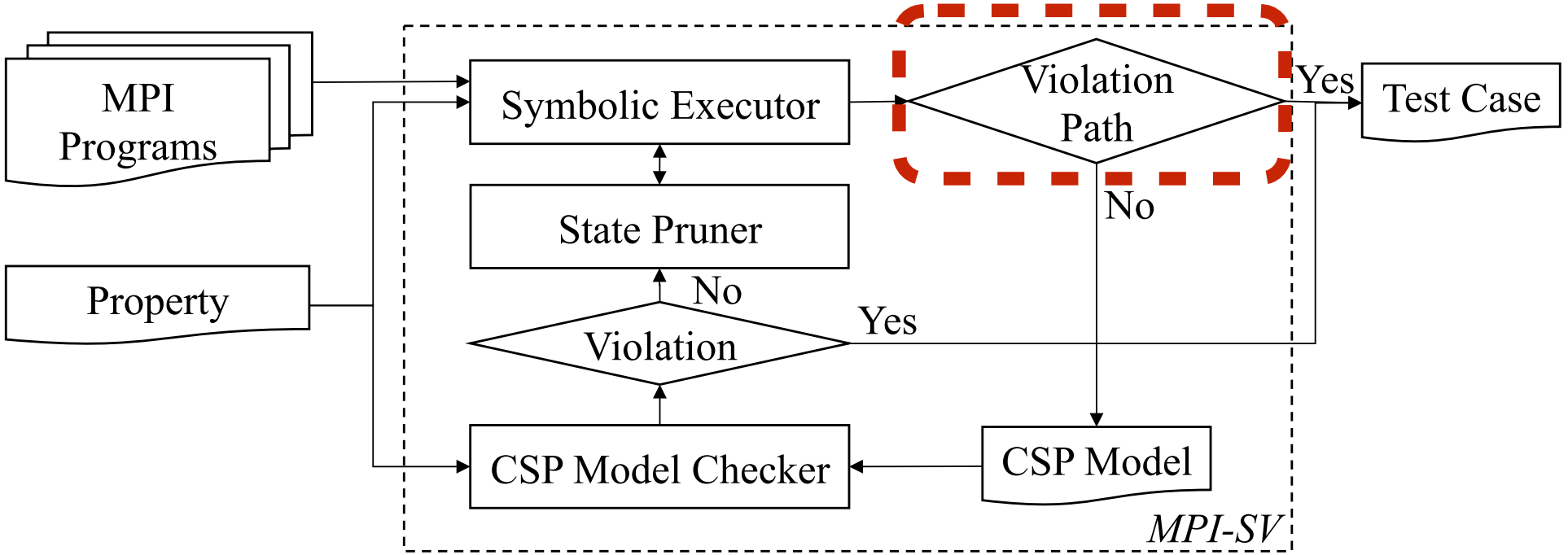

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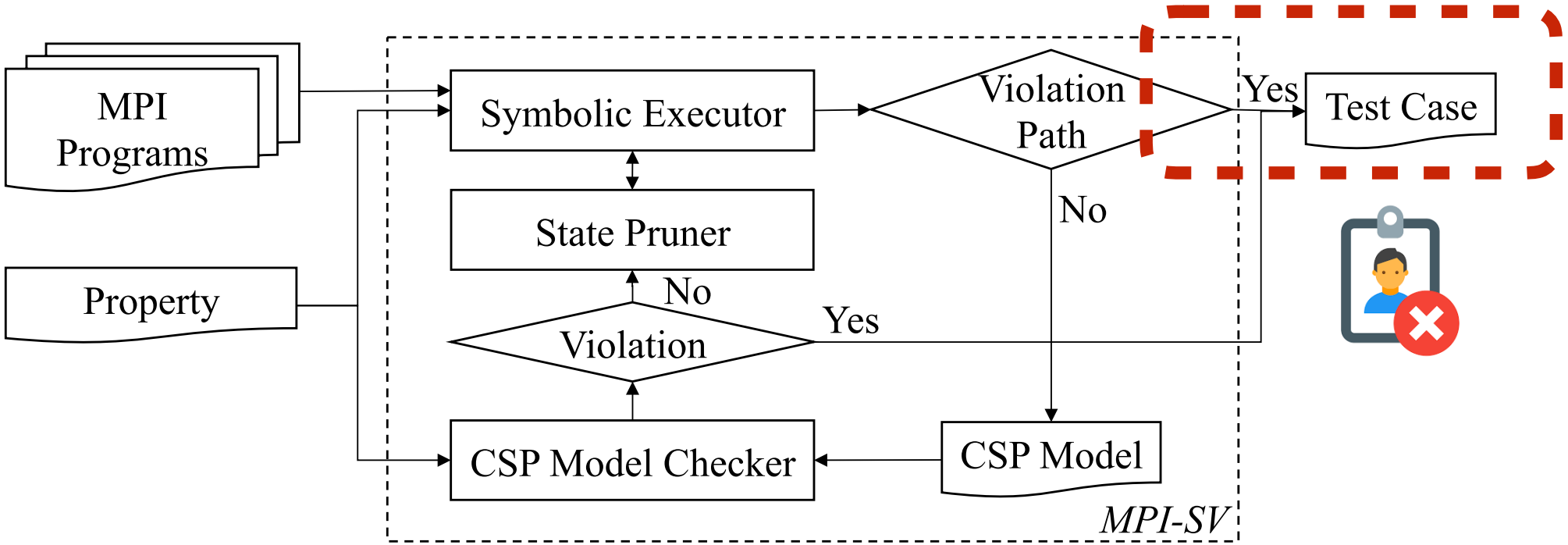

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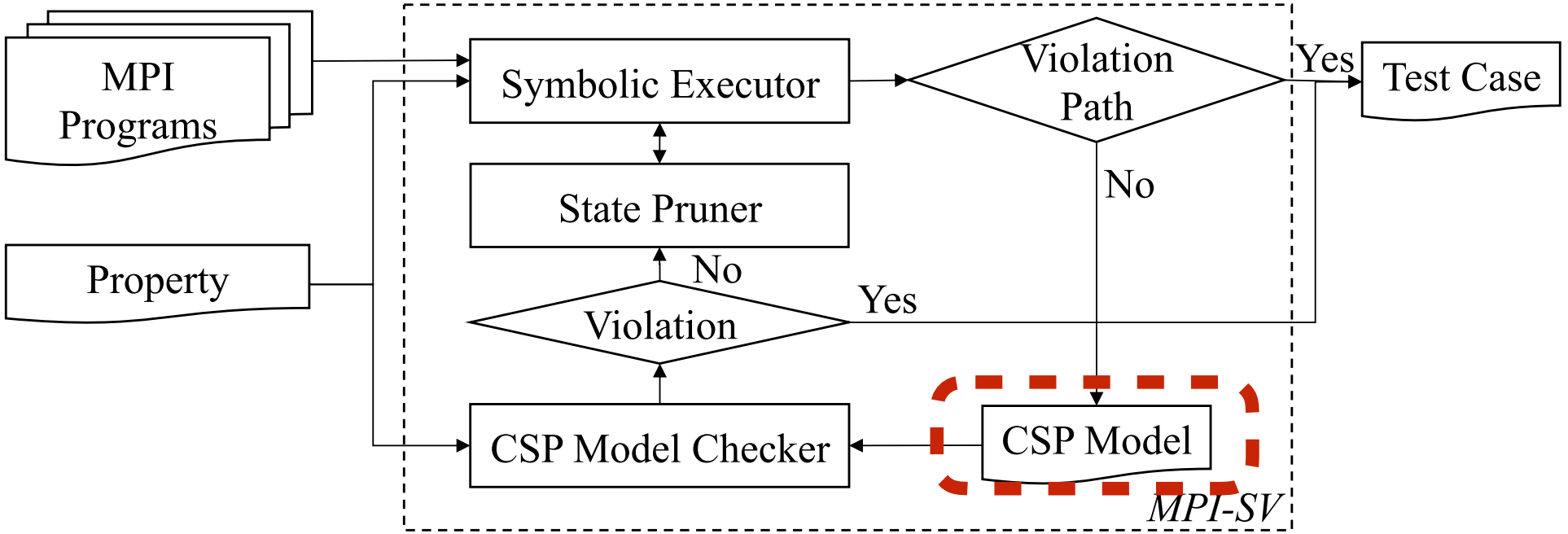

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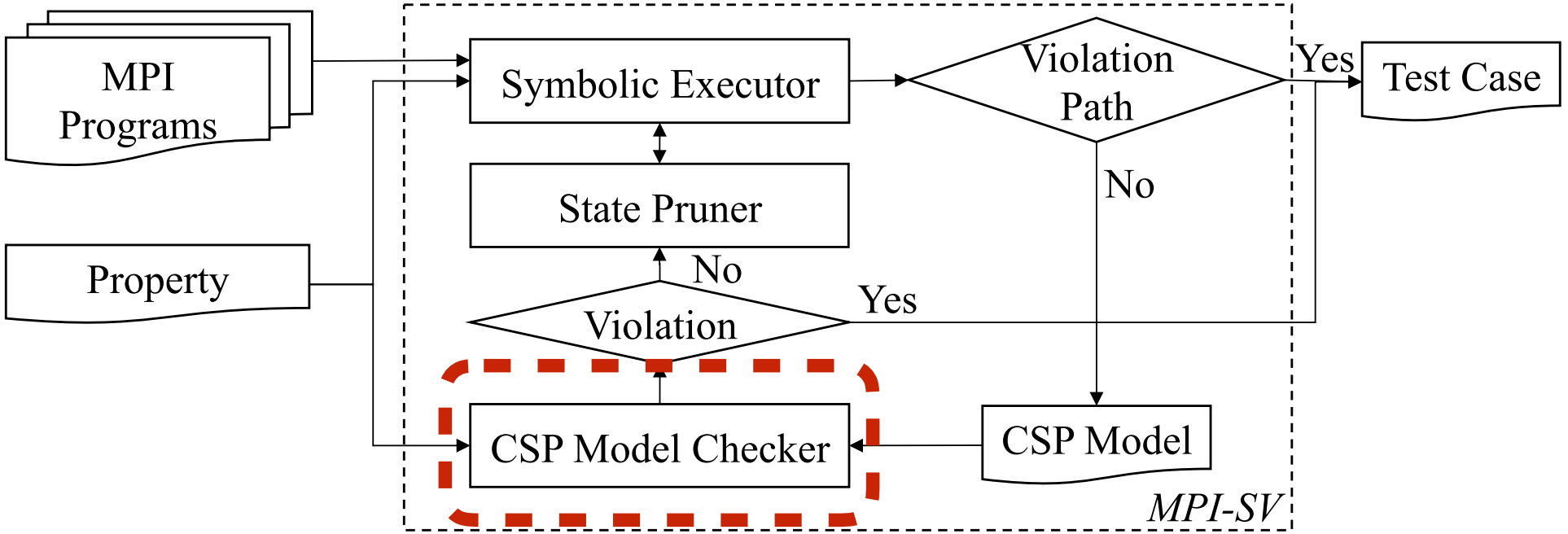

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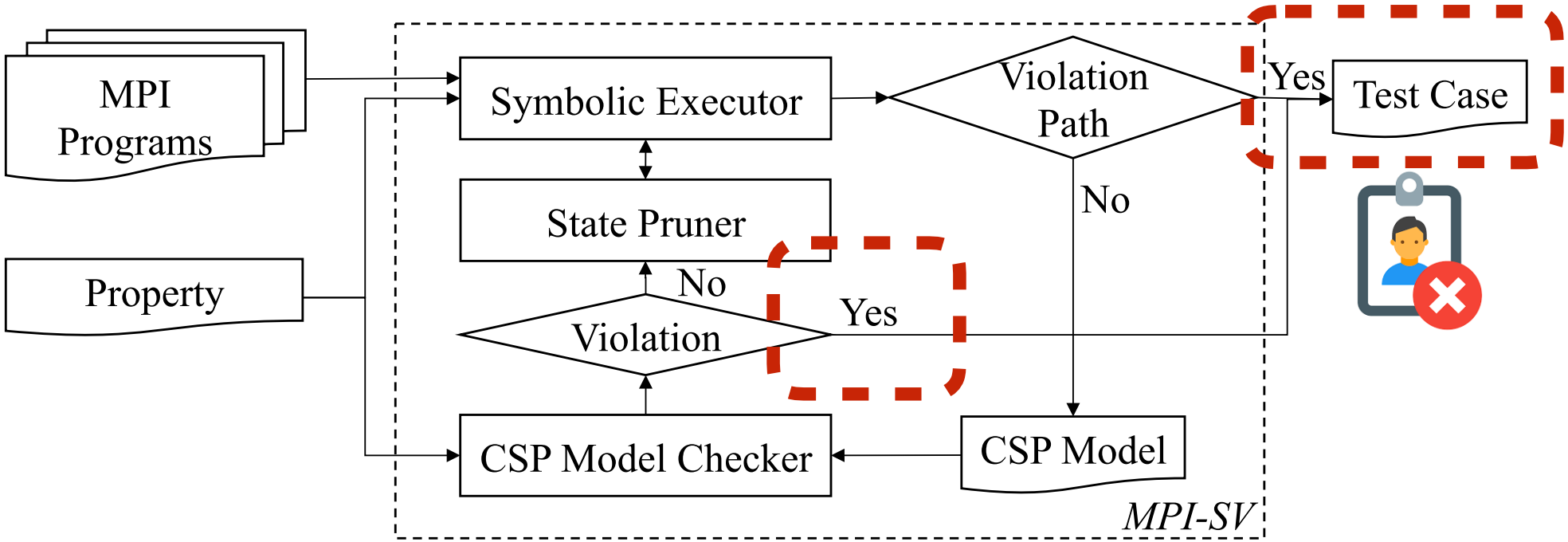
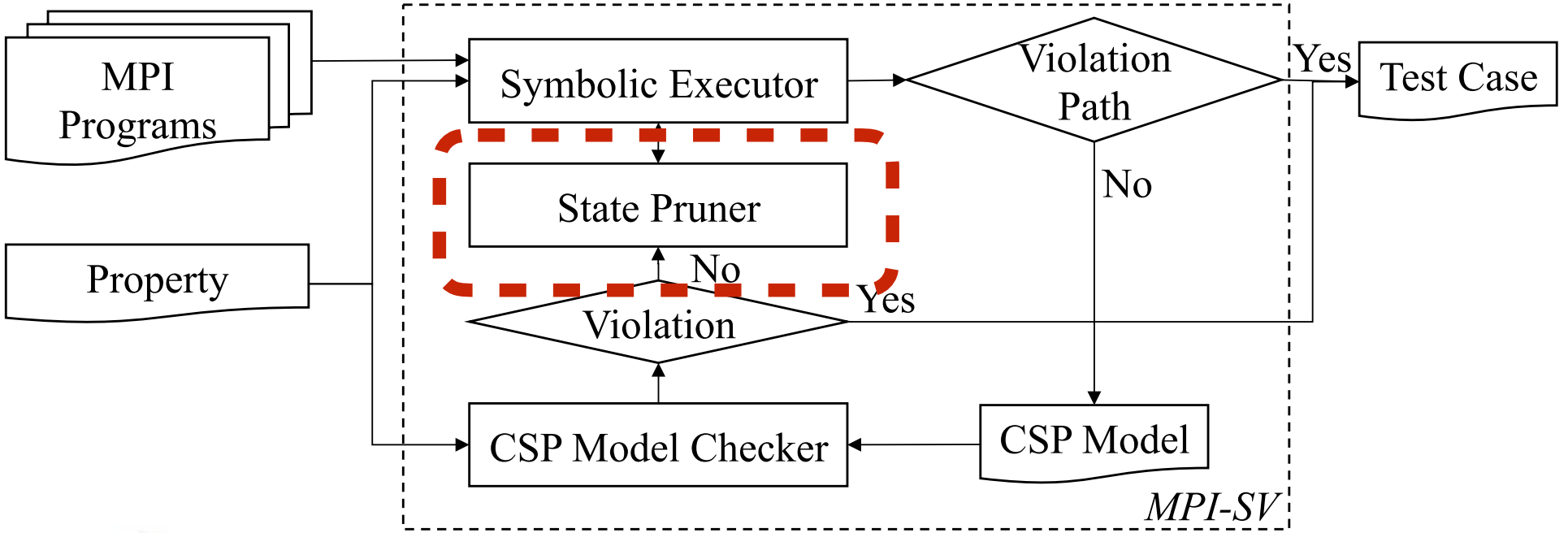


CSP modeling is sound and complete

Basic Framework



CSP modeling is sound and complete

High-Level View

Automatic Model Extraction

Boosting

Enlarge the scope of verifiable properties

Experiments

- Property
  - *Deadlock freedom*
  - *Non-reachability properties*
- Analyze each task (program/property) in one hour

Program	LOC	Description
DTG	90	Dependence transition group
Matmat	105	Matrix multiplication
Integrate	181	Integral computing
Diffusion2d	197	Simulation of diffusion equation
Gauss_elim	341	Gaussian elimination
Heat	613	Heat equation solver
Mandelbrot	268	Mandelbrot set drawing
Sorting	218	Array sorting
Image_mani	360	Image manipulation
DepSolver	8988	Multimaterial electrostatic solver
Kfray	12728	KF-Ray parallel raytracer
ClusterW	23265	Multiple sequence alignment
Total	**47354**	**12 open source MPI programs**

Main Results

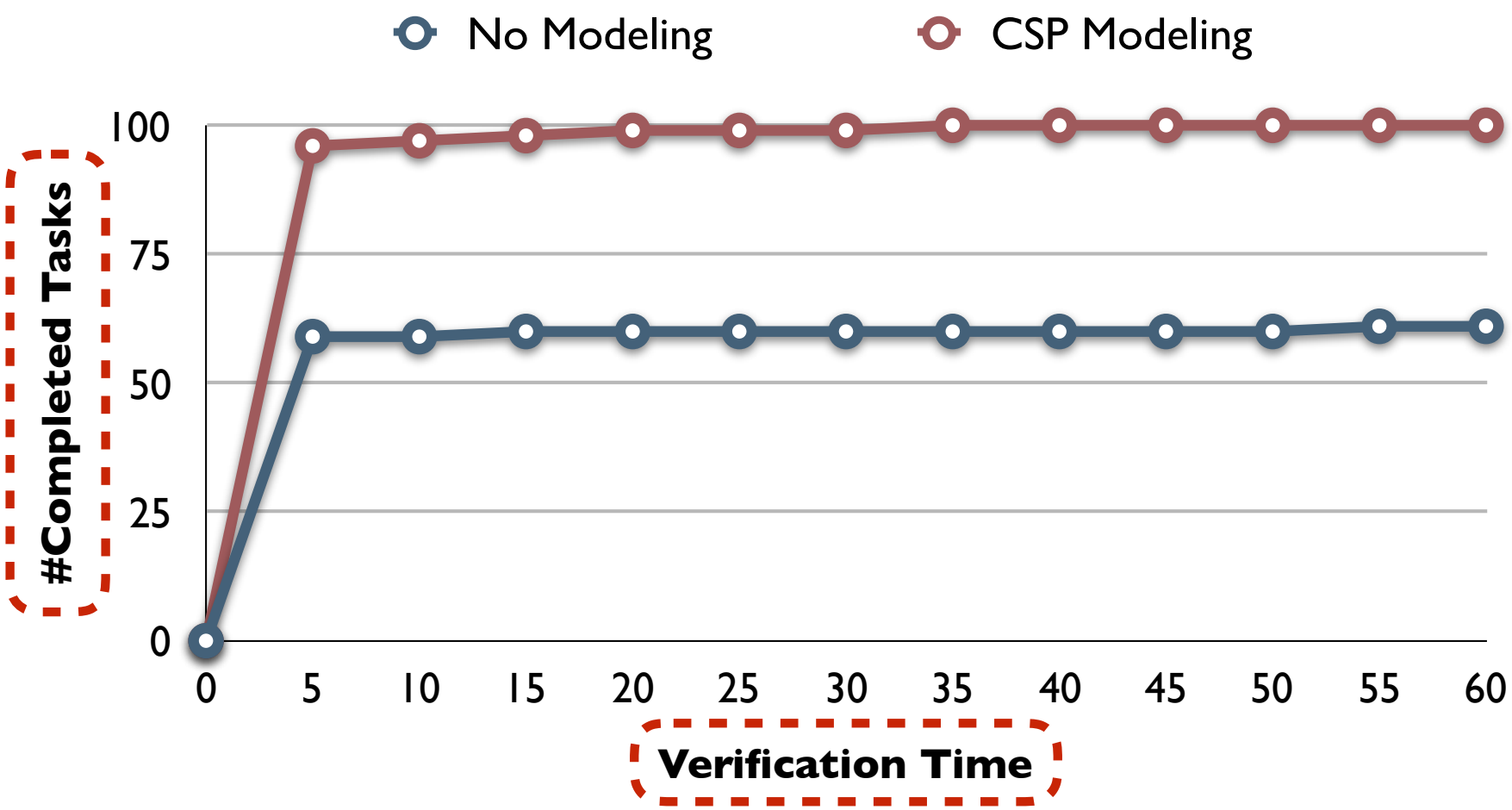
Program (#Procs)	T	Deadlock	Time(s)		#Iterations	
			Symbolic execution	Our approach	Symbolic execution	Our approach
DTG(5)	o	0	10.12	9.02	3	1
	m_1	0	13.69	9.50	10	2
	m_2	1	10.02	8.93	4	2
	m_3	1	10.21	9.49	4	2
	m_4	1	10.08	9.19	4	2
	m_5	1	9.04	9.29	2	2
Matmat*(4)	o	0	36.94	10.43	54	1
Integrate(6/8/10)	o	0/0/0	78.17/TO/TO	8.87/10.45/44.00	120/3912/3162	1/1/1
	m_1	0/0/-1	TO/TO/TO	49.94 /TO/TO	4773/3712/3206	32 /128/79
	m_2	1/1/1	9.35/9.83/9.94	9.39/10.76/44.09	2/2/2	2/2/2
Integrate*(4/6)	o	0/0	24.18/123.55	9.39/32.03	27/125	1/1
Diffusion2d(4/6)	o	0/0	106.86/TO	9.84/13.19	90/2041	1/1
	m_1	0/1	110.25/11.95	10.18 /13.81	90/2	1 /2
	m_2	0/1	3236.02/12.66	17.05 /14.38	5850/3	16/2
	m_3	0/0	TO/TO	19.26/199.95	5590/4923	16/64
	m_4	1/1	11.35 /11.52	11.14 /14.22	3/2	2 /2
	m_5	1/0	10.98/TO	10.85/13.44	2/1991	2/ 1
Gauss_elim(6/8/10)	o	0/0/0	TO/TO/TO	13.47/15.12/87.45	2756/2055/1662	1/1/1
	m_1	1/1/1	155.40/TO/TO	14.31/16.99/88.79	121/2131/559	2/2/2
Heat(6/8/10)	o	1/1/1	17.31/17.99/20.51	16.75 /19.27/22.75	2/2/2	1/1/1
	m_1	1/1/1	17.33/18.21/20.78	17.03 /19.75/23.16	2/2/2	1/1/1
	m_2	1/1/1	18.35/18.19/20.74	16.36 /19.53/23.07	2/2/2	1/1/1
	m_3	1/1/1	19.64/20.21/23.08	16.36/19.72/22.95	3/3/3	1/1/1
	m_4	1/1/1	22.9/24.73/27.78	16.4/19.69/22.90	9/9/9	1/1/1
	m_5	1/1/1	24.28/28.57/32.67	16.61/19.59/22.42	7/7/7	1/1/1
Mandelbrot(6/8/10)	o	0/0/-1	TO/TO/TO	117.68 / 831.87 /TO	500/491/447	9 / 9 /9
	m_1	-1/-1/-1	TO/TO/TO	TO/TO/TO	1037/1621/1459	173/227/246
	m_2	-1/-1/-1	TO/TO/TO	TO/TO/TO	1093/1032/916	178/136/90
	m_3	1/1/1	10.71/11.17/11.92	10.84/11.68/13.5	2/2/2	2/2/2
Mandelbort*(4/6)	o	0/0	68.09/270.65	12.65/13.21	72/240	2/2
Sorting*(4/6)	o	0/0	TO/TO	19.18/46.19	584/519	1/1
Image_mani(6/8/10)	o	0/0/0	97.69/118.72/141.87	18.68/23.84/27.89	96/96/96	4/4/4
	m_1	1/1/1	12.92/15.80/15.59	14.15/ 14.53 /16.86	2/2/2	2/2/2
DepSolver(6/8/10)	o	0/0/0	94.17/116.5/148.38	97.19/123.36/151.83	4/4/4	4/4/4
Kfray(6/8/10)	o	0/0/0	TO/TO/TO	51.59/68.25/226.96	1054/981/1146	1/1/1
	m_1	1/1/1	52.15/53.50/46.83	53.14/69.58/229.97	2/2/2	2/2/2
	m_2	-1/-1/-1	TO/TO/TO	TO/TO/TO	1603/1583/1374	239/137/21
	m_3	1/1/1	51.31/43.34/48.33	50.40 /71.15/230.18	2/2/2	2/2/2
Kfray*(4/6)	o	0/0	TO/TO	53.44/282.46	1301/1575	1/1
Clustalw(6/8/10)	o	0/0/0	TO/TO/TO	47.28/79.38/238.37	1234/1105/1162	1/1/1
	m_1	0/0/0	TO/TO/TO	47.94/80.10/266.16	1365/1127/982	1/1/1
	m_2	0/0/0	TO/TO/TO	47.71/90.32/266.08	1241/1223/915	1/1/1
	m_3	1/1/1	895.63/TO/TO	149.71/1083.95/301.99	175/1342/866	5/17/2
	m_4	0/0/0	TO/TO/TO	47.49/79.94/234.99	1347/1452/993	1/1/1
	m_5	0/0/0	TO/TO/TO	47.75/80.33/223.77	1353/1289/1153	1/1/1

111 verification tasks

	No Modeling	CSP Modeling	Speedup
Finished	61 (55%)	100 (90%)	
Deadlock	44	48	>5X
No Deadlock	17	52	>19X

MPI-SV is more effective and efficient than pure symbolic execution

The Progress Distribution



MPI-SV can complete more tasks under the same time threshold

Conclusion

High Performance Computing

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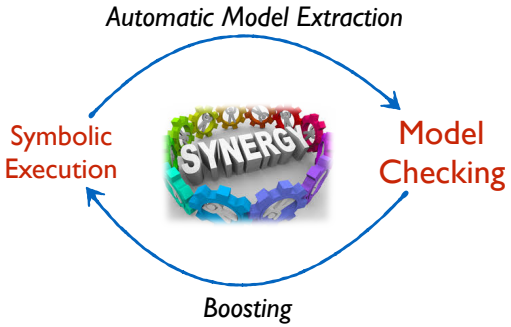
High-Level View



Enlarge the scope of verifiable properties

21

Existing Work of MPI Verification

	Automation	Input Coverage	Non-Blocking
CIVL(TASS)	Yes	Yes	No
MOPPER	Yes	No	Yes
MPI-SPIN	No	Yes	Yes
MPI-SV	**Yes**	**Yes**	**Yes**

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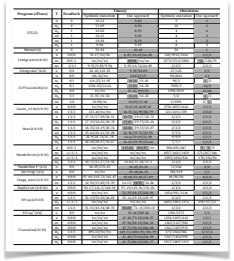
Main Results



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Thank you!

Q&A

https://mpi-sv.github.io