lecture 24:
testing OpenFlow applications
5590: software defined networking

anduo wang, Temple University
TTLMAN 401B, R 17:30-20:00

A NICE Way to Test OpenFlow Applications

https://www.usenix.org/conference/nsdi12/technical-sessions/presentation/canini

SDN and software faults (bugs)

SDN raises the risks of bugs?

- wide range of functionality through software
  - diverse collection of network operators — 3rd party

SDN depends on reliable control software

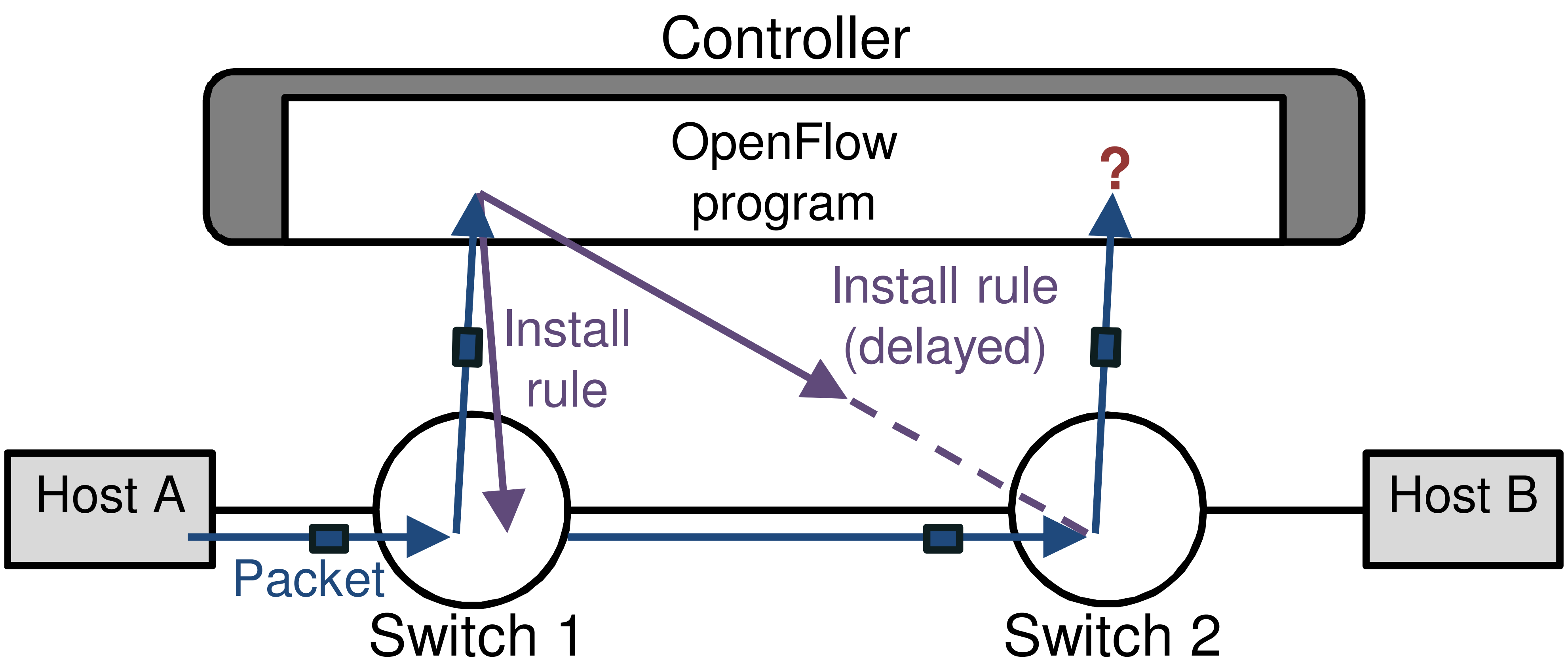
- testing OpenFlow applications

bugs in OF applications

for each event, a controller handler installs rules or collects traffic statistics

- conceptually centralized
- but the system is inherently distributed and asynchronous
- an OF application that works correctly most of the time can misbehave under certain event orderings

example bug


Controller
OpenFlow
program
?
Install
rule
Install rule
(delayed)
Host A
Packet
Switch 1
Switch 2
Host B

the challenges

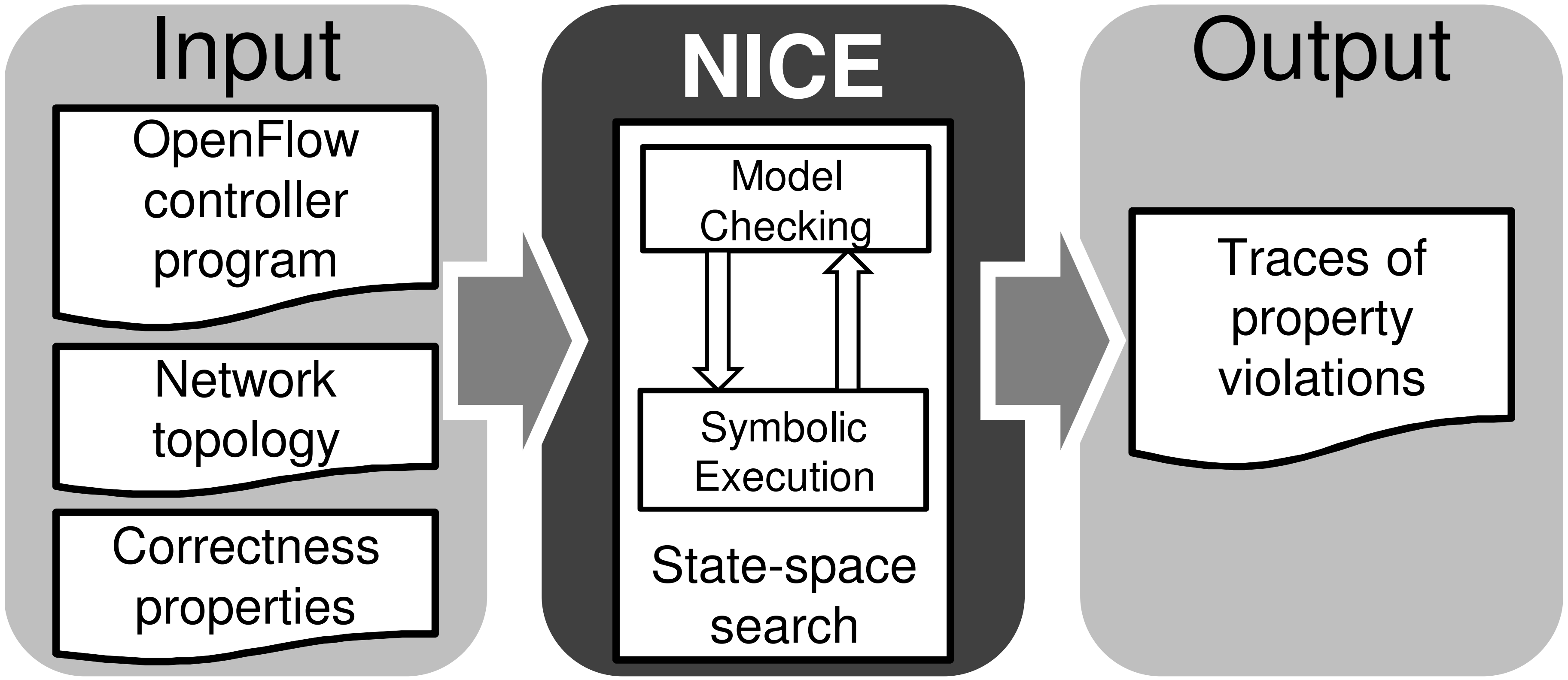
OF applications execute in a larger environment

- end-hosts send and receive traffic
- switches process packets, install rules, generate events

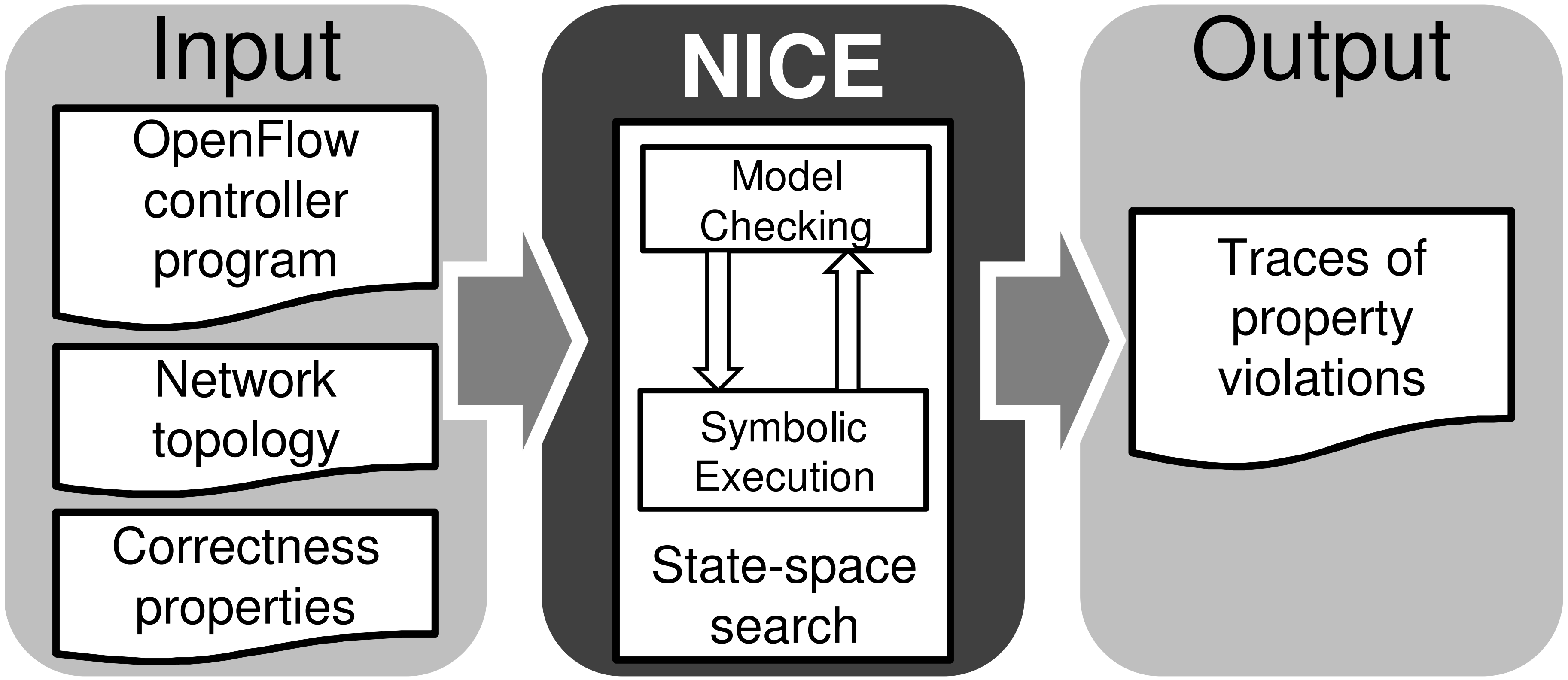
large space of

- switch state
  - switches run their own programs: state for packet processing, counters, timers, priority
- input packets
  - OF match fields: MAC, IP (source, destination), port …
- event ordering
  - packet arrivals, topology changes …

NICE


Input
OpenFlow controller program
Network topology
Correctness properties
NICE
Model Checking
Symbolic Execution
State-space search
Output
Traces of property violations

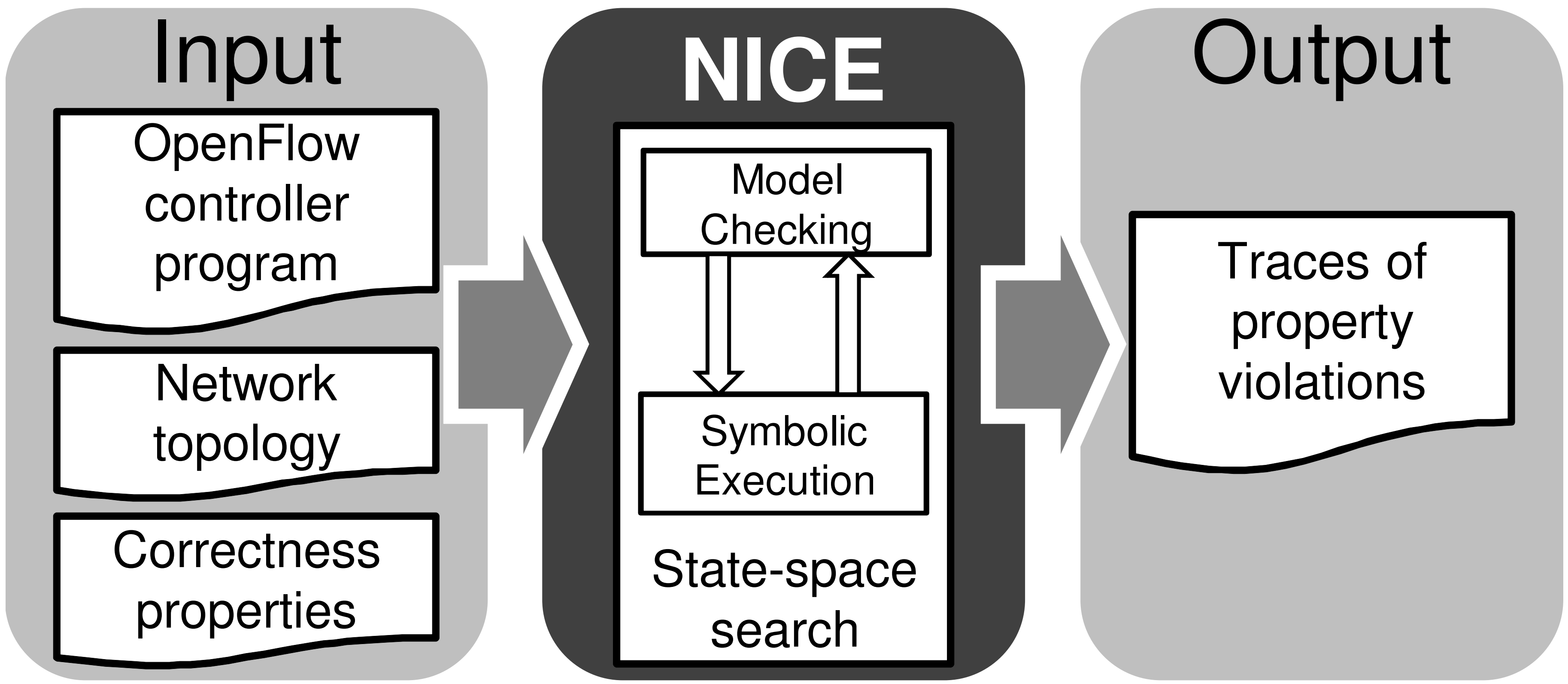
NICE



NICE approach

- test un-modified controller programs, by
- automatically generate carefully-crafted streams of packets under many possible event interleavings

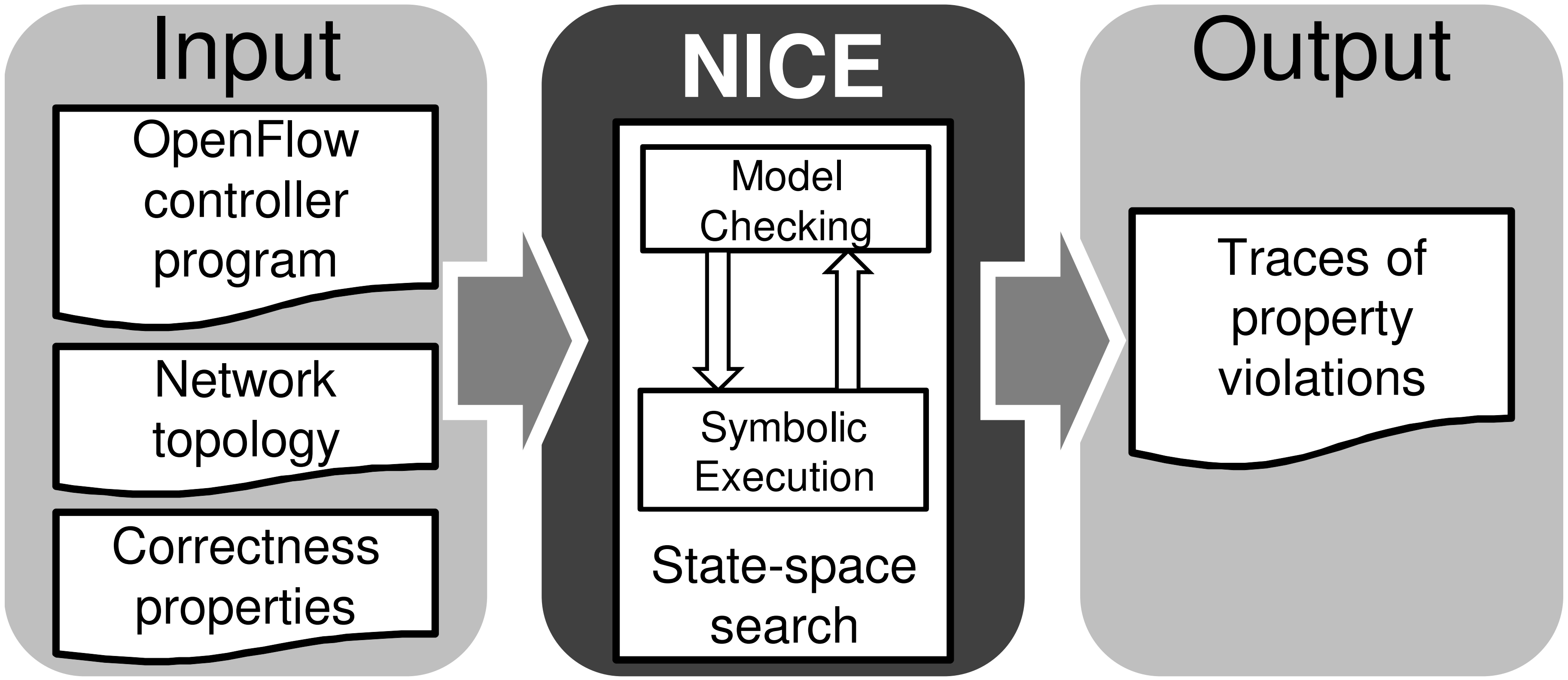
NICE



address large space of switch state

- simplified switch / host models

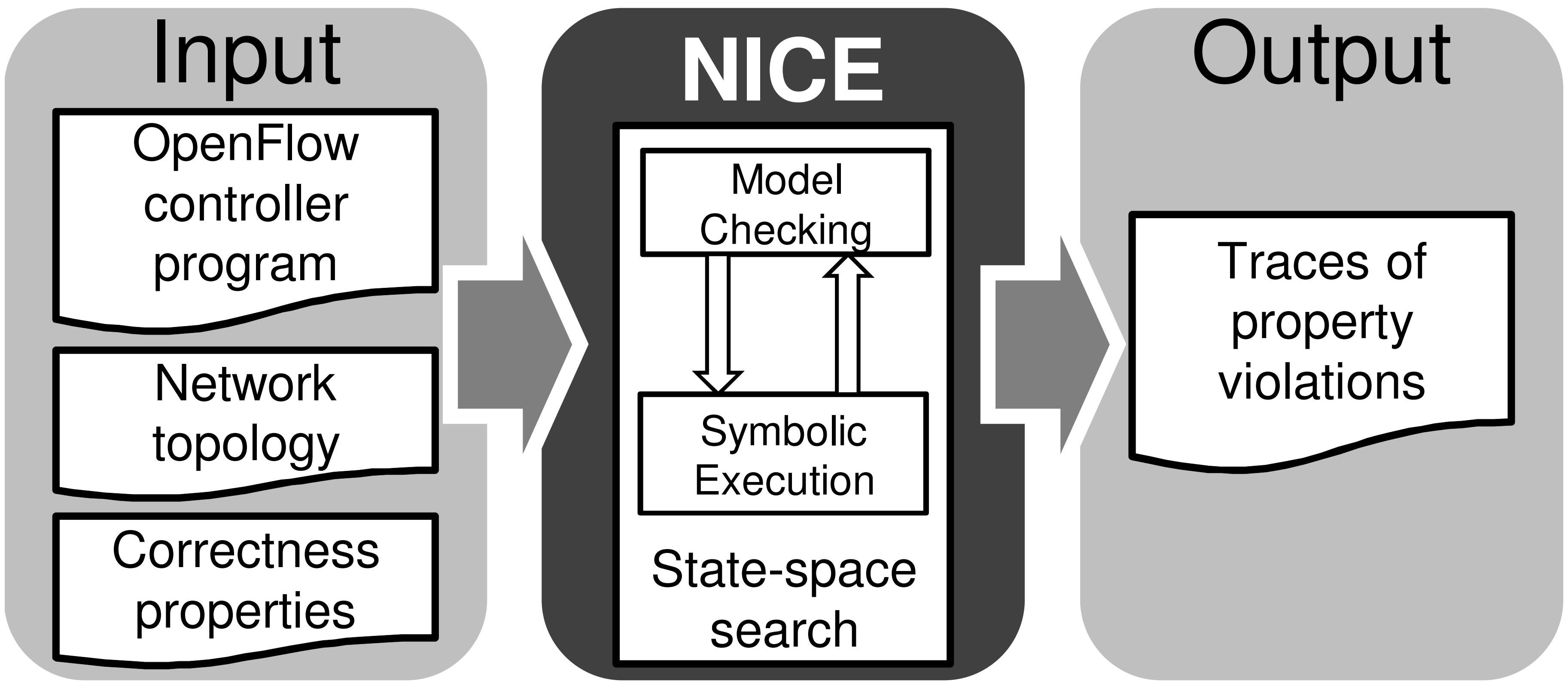
NICE



address large space of input packets

- symbolic executing packet-arrival handlers
  - identifies equivalence classes of packets
  - feeds the network a representative concrete packet

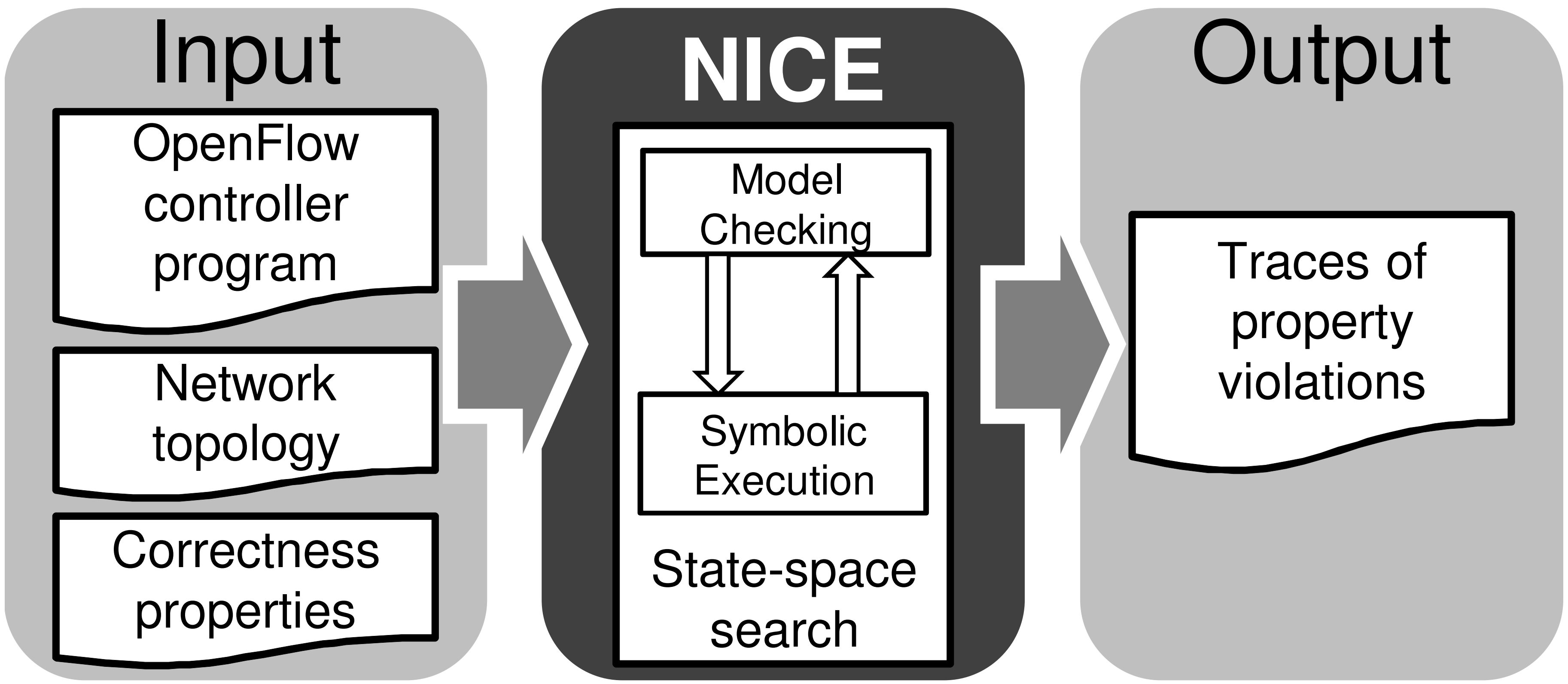
NICE



address large space of event ordering

- domain specific search strategies that are likely to uncover bugs

NICE



model checking — systematically explore execution paths, customized with

- simplified model of switches, hosts
- representative packet inputs by symbolic execution
- search strategy by domain knowledge

transition model — controller

controller program

- a set of event handlers
  - events: packet arrivals, topology changes
- state
  - global variables (ctrl_state)
- transition
  - treat each handler a transition
  - (event handler, concrete input)

transition model — controller

controller program

- a set of event handlers
  - events: packet arrivals, topology ch
- state
  - global variables (ctrl_state)
- transition
  - treat each handler a transition
  - (event handler, concrete input)

```
ctrl_state = {} # State of the controller is a global variable (a hashtable)
def packet_in(sw_id, inport, pkt, bufid): # Handles packet arrivals
  mactable = ctrl_state[sw_id]
  is_bcast_src = pkt.src[0] & 1
  is_bcast_dst = pkt.dst[0] & 1
  if not is_bcast_src:
    mactable[pkt.src] = inport
  if (not is_bcast_dst) and (mactable.has_key(pkt.dst)):
    outport = mactable[pkt.dst]
    if outport != inport:
      match = {DL_SRC: pkt.src, DL_DST: pkt.dst, ↩
          DL_TYPE: pkt.type, IN_PORT: inport}
      actions = [OUTPUT, outport]
      install_rule(sw_id, match, actions, soft_timer=5, ↩
          hard_timer=PERMANENT) # 2 lines optionally
      send_packet_out(sw_id, pkt, bufid) # combined in 1 API
      return
  flood_packet(sw_id, pkt, bufid)
def switch_join(sw_id, stats): # Handles when a switch joins
  if not ctrl_state.has_key(sw_id):
    ctrl_state[sw_id] = {}
def switch_leave(sw_id): # Handles when a switch leaves
  if ctrl_state.has_key(sw_id):
    del ctrl_state[sw_id]
```

transition model — switches

switch software

- complex but irrelevant

state

- values of all variables

transition

- identify the portions of the code that process packets or control (OpenFlow) messages

transition model — switches

communication channels

- first-in, first-out buffer

transition driven by data packets and OF messages

state

- process_pkt
- process_of

merging equivalent flow tables

- canonical representation, unique order of rules

symbolic executing event handlers

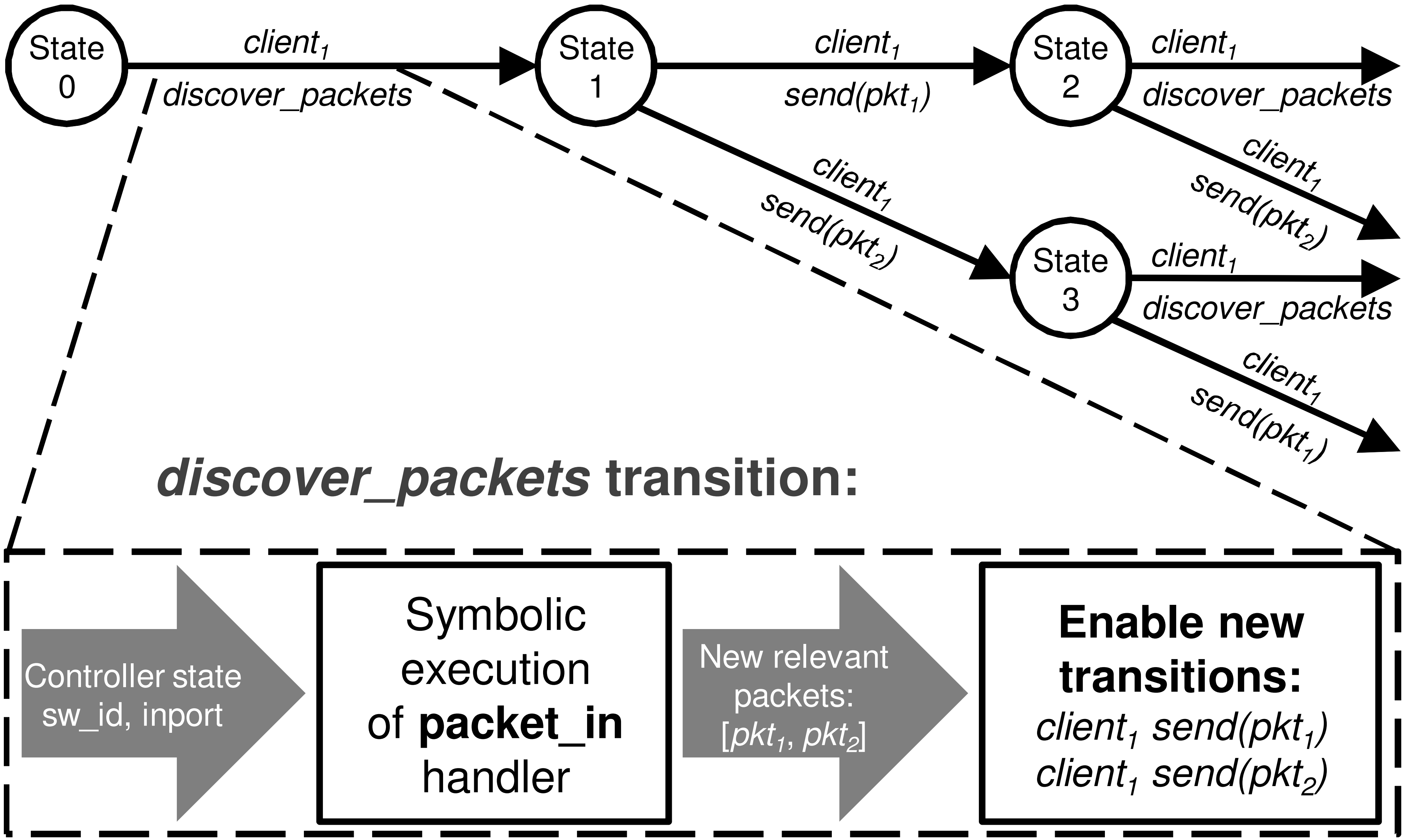
symbolic execution is the natural choice for exploring code paths, but

- limitation
  - NOT scale well because the number of code paths can grow exponentially with
    - branches, inputs

challenges of symbolic executing OpenFlow Apps

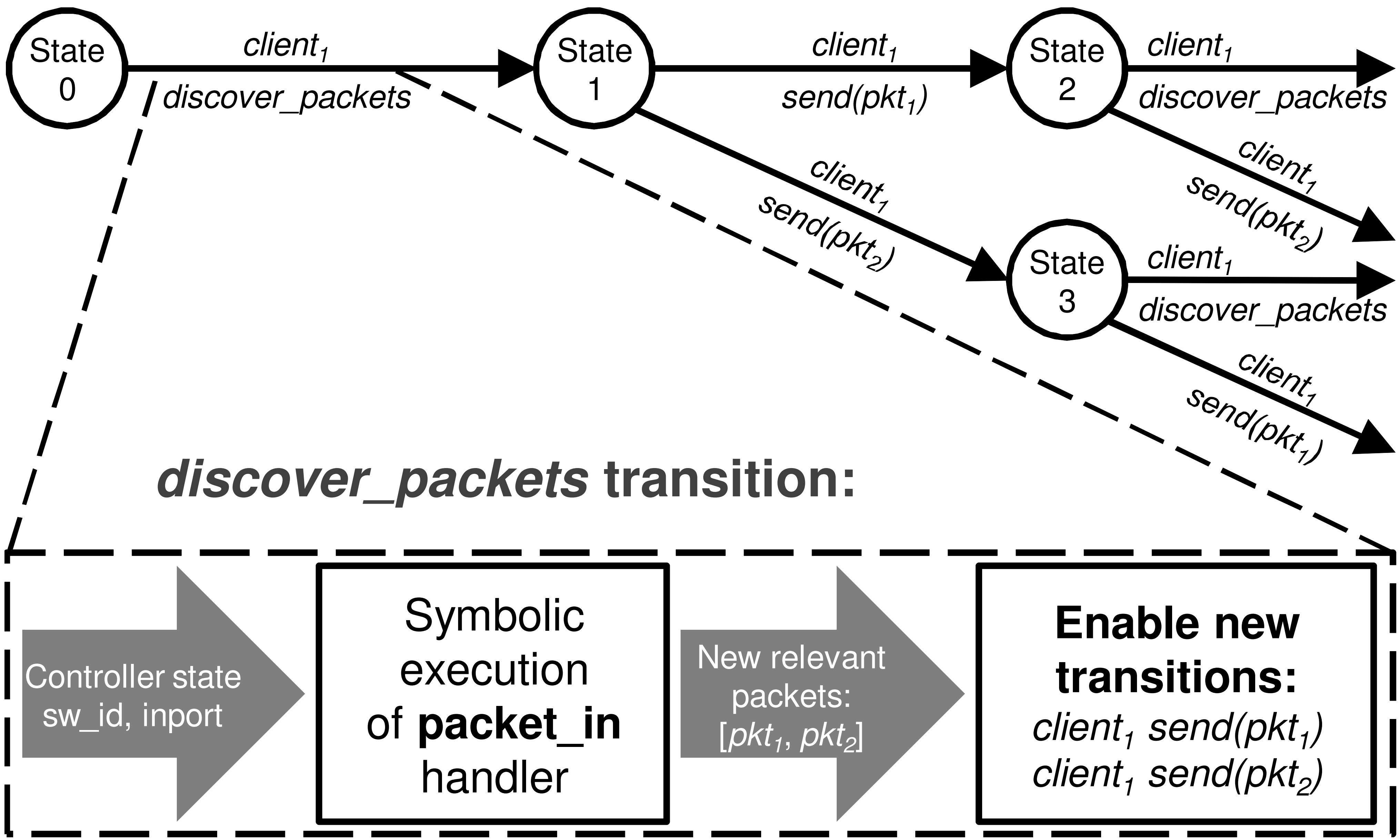
- diverse inputs to packet_in handler
  - solution: symbolic packets
- controller state
  - solution: concrete (rather than symbolic) representation

SE + model checking



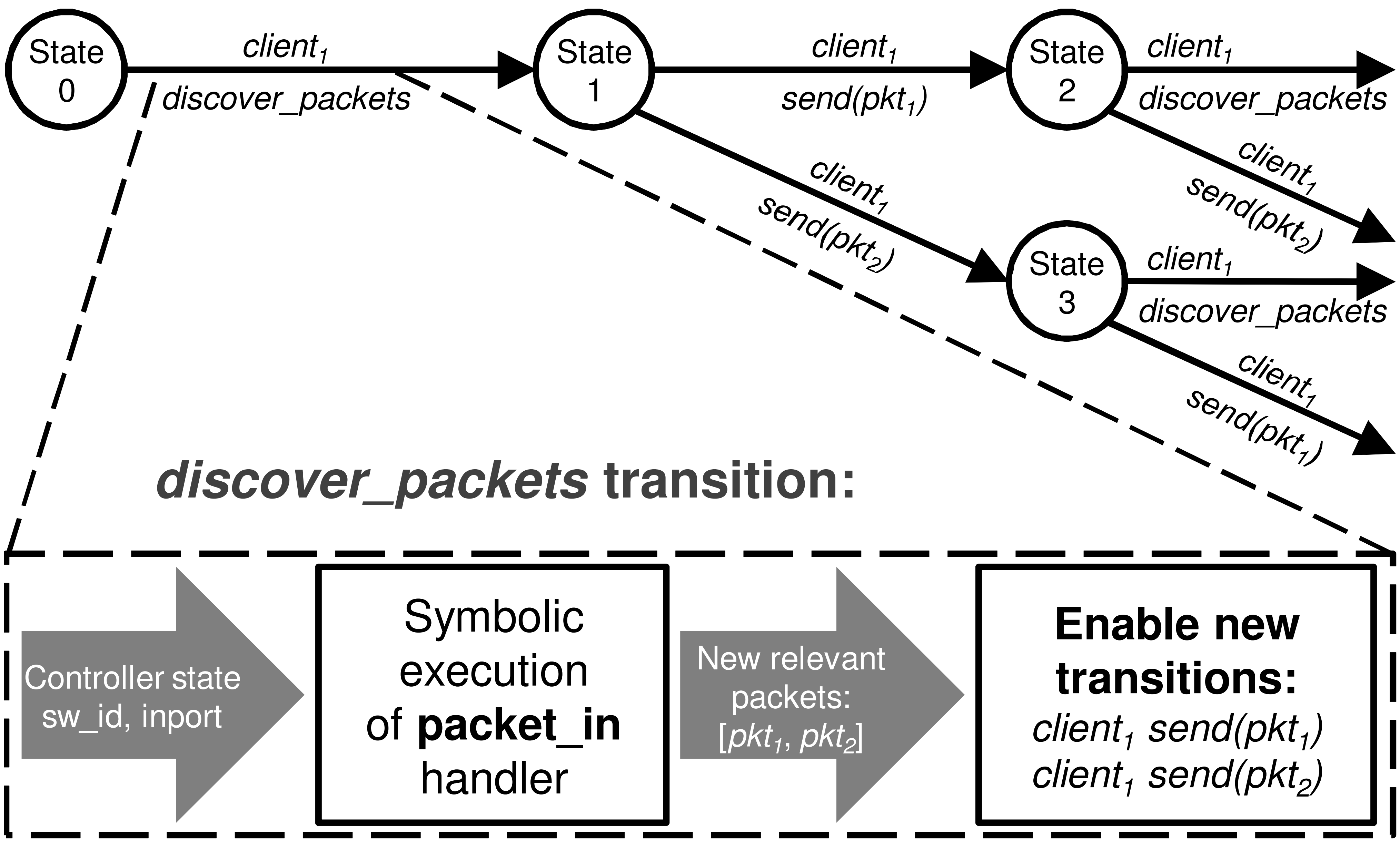
- model checker runs until
  - visiting all the states
  - or, detecting a first error

SE + model checking



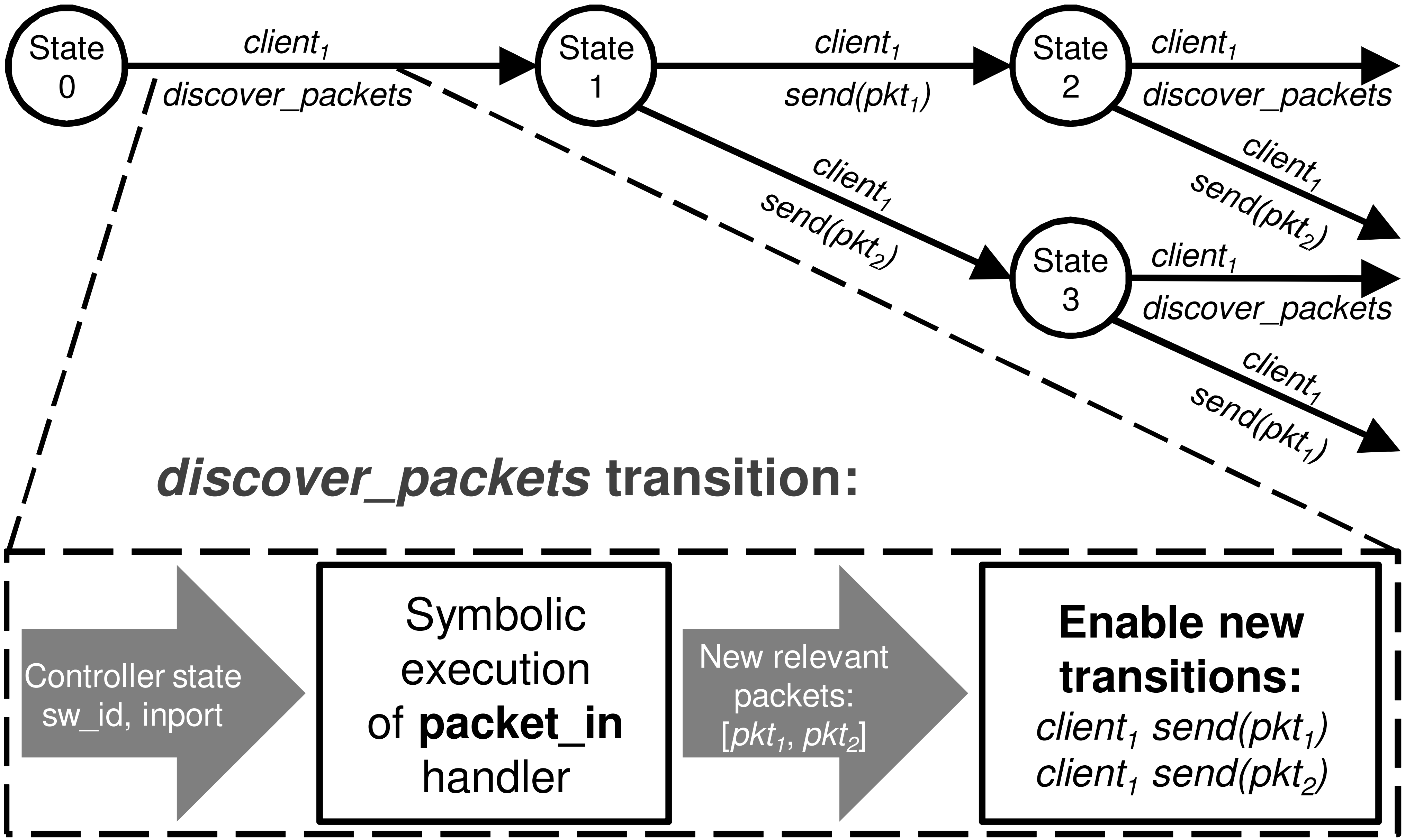
- concrete controller state
  - embed the controller state in symbolic execution
  - use concrete variables rather than symbolic ones

SE + model checking



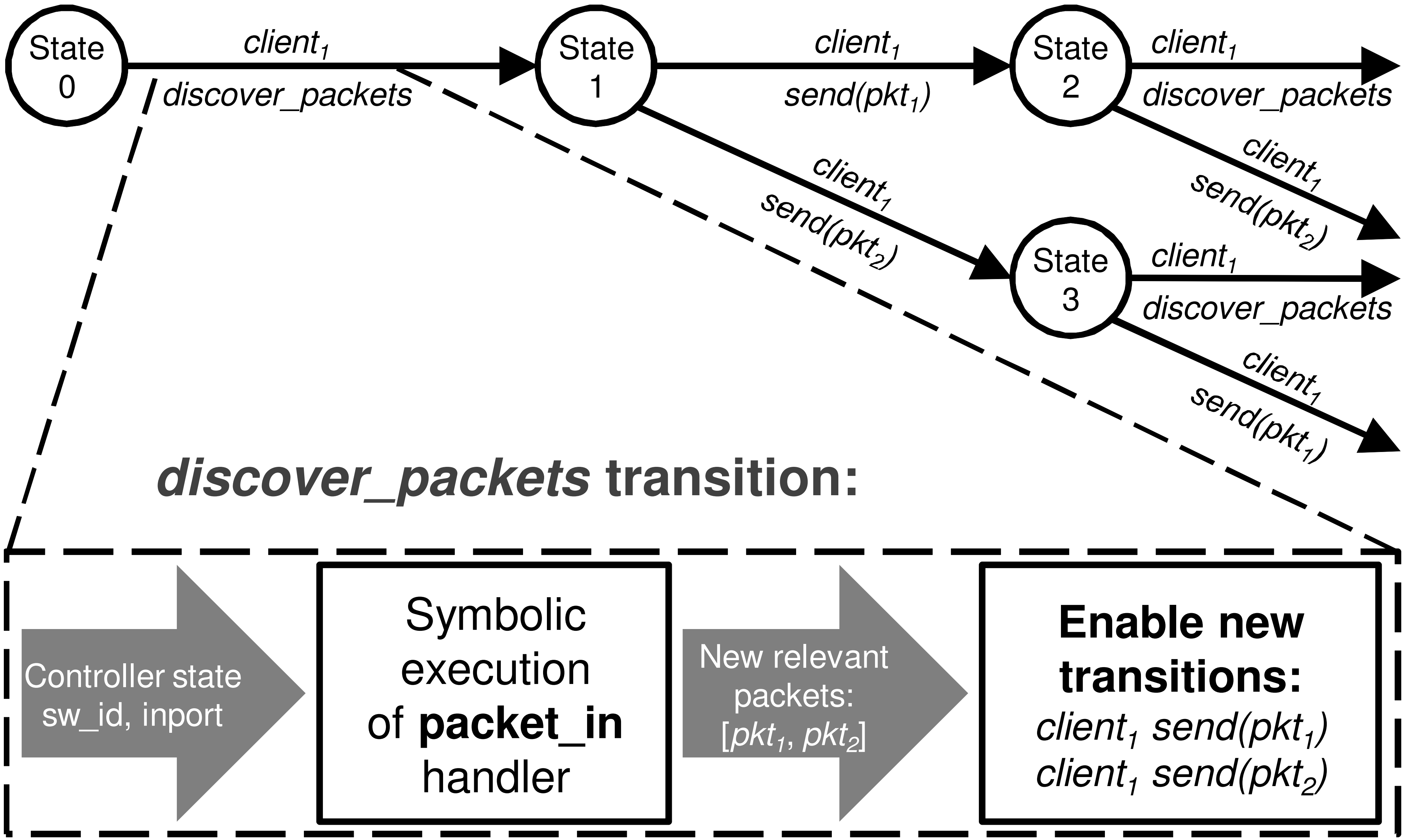
- at any controller state, add a special transition
  - discover_packets
    - identify the packets that each client should send
    - symbolically executes packet_in handler

SE + model checking



- at any controller state, add a special transition
  - discover_states
    - similar SE technique to deal with traffic statistics

SE + model checking



- for every code path
  - instantiate one concrete packet

search strategies

use domain knowledge to reduce the space of event ordering

- focus on those that are likely to uncover bugs

PKT-SEQ: relevant packet sequences

- discover_packets and send can generate a unbounded tree of packet sequences
- bound the tree
  - depth: maximum length of the sequence
  - length of a packet burst: maximum number of outstanding packets

NO-DELAY: instantaneous rule update

- treat communication between a switch and the controller an atomic action

search strategies — continued

UNUSAL: unusual delay and reordering

- eg: if controller event handler installs rules in switches 1,2,and 3; explores transitions that reverse the order by allowing switch 3 to install its rule first

FLOW-IR: flow independence reduction

- handling of one group is not affected by the presence of another
- explore only one relative ordering between the events affecting each group

correctness properties

correctness properties

correctness property in NICE

- a module defines robust communication delays
  - e.g., intentionally wait until a "safe" time to test the property to prevent natural delays from erroneously triggering false violation

correctness properties

correctness property in NICE

- a module defines robust communication delays
  - e.g., intentionally wait until a "safe" time to test the property to prevent natural delays from erroneously triggering false violation

a library

- no forwarding loops
- no black holes
- direct paths
  - once a packet reaches its destination, future packets of the same flow do not go to the controller
- no forgotten packets
  - all switch buffers are empty at the end of system execution

implementation highlights

NICE consists of three parts

- a model checker; a symbolic execution engine; a collection of models

implementation highlights

NICE consists of three parts

- a model checker; a symbolic execution engine; a collection of models

model checker

- system state checkpoint and restore
  - remember the sequence of transition that created the state and restore it by replaying such sequence
- state-matching
  - compare and store the hashes of the explored state

implementation highlights

symbolic execution engine

- a concolic-execution engine, a derivative technique of SE
  - execute code with concrete instead of symbolic inputs
    - avoids modify Python interpreter, still tracks constraints along the code path
- implement in Python a new "symbolic integer" data type to track constraints; a new arrays of the symbolic integers
- pre-processing — normalize and instrument
  - convert Python app into abstract syntax tree (AST)
  - manipulate the AST tree:
    - split composite branch of predicates
    - move function calls before conditional expression
    - instrument branches to inform the councilor engine on which branch is take
    - intercept and remove nondeterminism
    - …

performance

NICE-MC: full search model checking without SE
NO-SWITCH-REDUCTION: model checking without simplified switch model

	NICE-MC			NO-SWITCH-REDUCTION			
Pings	**Transitions**	**Unique states**	**CPU time**	**Transitions**	**Unique states**	**CPU time**	ρ
2	470	268	0.94 [s]	760	474	1.93 [s]	0.38
3	12,801	5,257	47.27 [s]	43,992	20,469	208.63 [s]	0.71
4	391,091	131,515	36 [m]	2,589,478	979,105	318 [m]	0.84
5	14,052,853	4,161,335	30 [h]	-	-	-	-

performance

NICE-MC: full search model checking without SE
NO-SWITCH-REDUCTION: model checking without simplified switch model

	NICE-MC			NO-SWITCH-REDUCTION			
Pings	**Transitions**	**Unique states**	**CPU time**	**Transitions**	**Unique states**	**CPU time**	ρ
2	470	268	0.94 [s]	760	474	1.93 [s]	0.38
3	12,801	5,257	47.27 [s]	43,992	20,469	208.63 [s]	0.71
4	391,091	131,515	36 [m]	2,589,478	979,105	318 [m]	0.84
5	14,052,853	4,161,335	30 [h]	-	-	-	-

- setup
  - host A pings B, which replies with a packet to A, the controller runs MAC learner
  - Linux 2.6.32, 64GB RAM, clock speed of 2.6GHz
- measure metrics as input packets (concurrent pings) increase
  - number of transitions and unique states
  - execution time

performance

NICE-MC: full search model checking without SE
NO-SWITCH-REDUCTION: model checking without simplified switch model

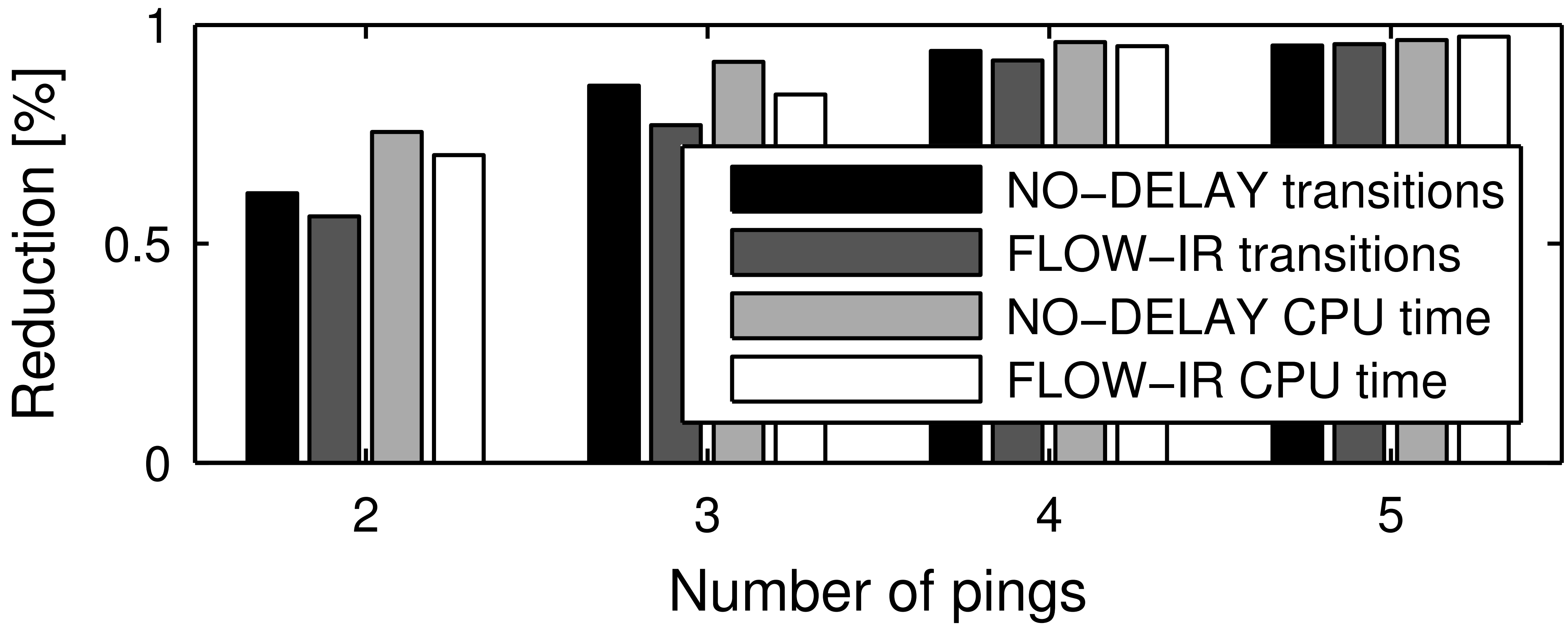
	NICE-MC			NO-SWITCH-REDUCTION			
Pings	**Transitions**	**Unique states**	**CPU time**	**Transitions**	**Unique states**	**CPU time**	ρ
2	470	268	0.94 [s]	760	474	1.93 [s]	0.38
3	12,801	5,257	47.27 [s]	43,992	20,469	208.63 [s]	0.71
4	391,091	131,515	36 [m]	2,589,478	979,105	318 [m]	0.84
5	14,052,853	4,161,335	30 [h]	-	-	-	-

- setup
  - host A pings B, which replies with a packet to A, the controller runs MAC learner
  - Linux 2.6.32, 64GB RAM, clock speed of 2.6GHz
- measure metrics as input packets (concurrent pings) increase
  - number of transitions and unique states
  - execution time

$$\rho = \frac{Unique(\text{NO-SWITCH-REDUCTION}) - Unique(\text{NICE-MC})}{Unique(\text{NO-SWITCH-REDUCTION})}$$

state-space search reduction

reduction relative to full-search NICE-MC:
state space is significant



- reduction relative to full-search NICE-MC
  - state space reduction is significant
  - for three pings, switch model + heuristics results in a 28-fold reduction

comparison with SPIN

on full search

- SPIN outperforms NICE

state-space explosion

- NICE outperforms SPIN
- SPIN
  - with 7 pings, SPIN runs out of memory
  - SPIN partial-order reduction decreases the growth rate of explored transition by 18%
- NICE
  - simplified switch models, hashing explored states, search strategies