Formal Analysis of a Fault-Tolerant Routing Algorithm for a Network-on-Chip

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Motivating Application: Cyber-Physical Systems

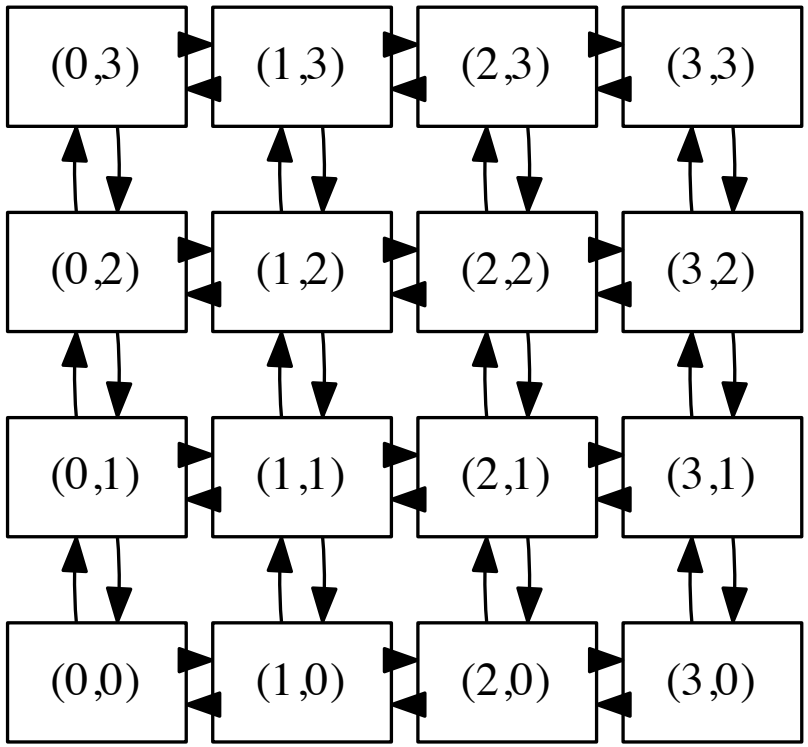
- A *Cyber-Physical System* (CPS) has tight interaction between computation and physical processes.
- Example: *Electronic control units* (ECUs) control everything (engine, brakes, drive-train, etc.) in automotive systems.
- An ECU uses some sensors and actuators to control a part of the physical system through a feedback loop.
- ECUs statically tied to a processor cannot share computing power and are subject to faults.
- Prof. Tomohiro Yoneda's research group at National Institute of Informatics (Japan) proposed a Network-on-Chip (NoC) approach for flexible mapping of ECUs onto the available processors.
- In this talk: experience report about the verification of different routing models with CADP.

Related Work

- precomputed route tables: not adaptive, only permanent faults
- Glass/Ni algorithm: faults of complete routers rather than single links
- GeNoC: formal proofs with ACL2
- ANOC/CHP: verified with CADP, but no fault-tolerance

Network-on-Chip Topology

- Two-dimensional mesh
- Nodes labeled by their position "(x, y)"
- Multi-flit wormhole routing



Properties for Verification

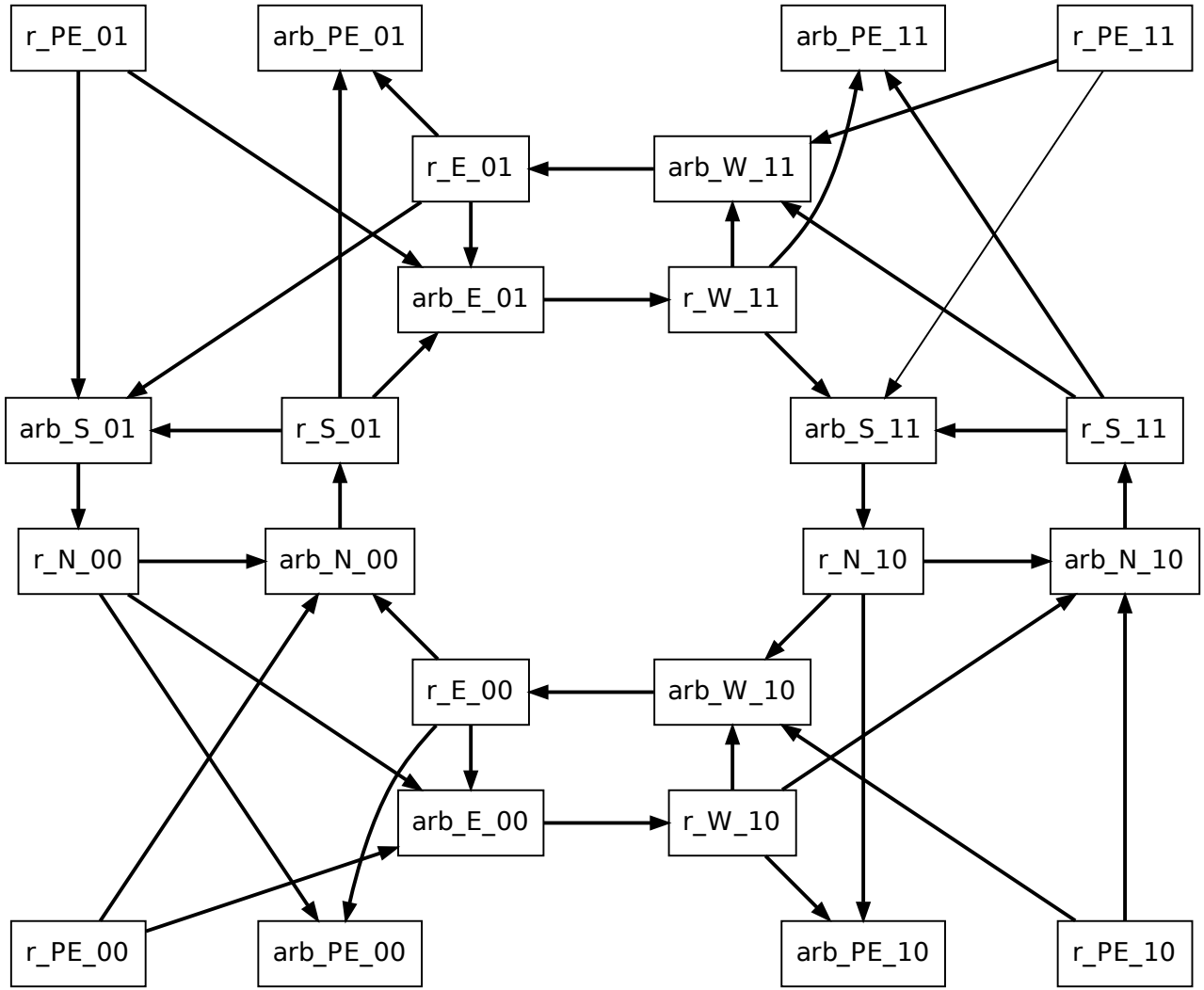
- The link-fault tolerant routing algorithm is free of deadlocks.
- Given at most one failure link, it is never the case that a router is unable to route a packet.
- Given at most one failure link, a packet never gets dropped when it is the only one packet in the network.

Plan of the Presentation

- Two-By-Two Mesh Architecture
- Principles of the Routing Algorithm
- Counter-Clockwise Routing Model
- Structural Abstraction to Reduce the State Space
- Data-Abstractions to Reduce the State Space
- Verification Results
- Conclusion

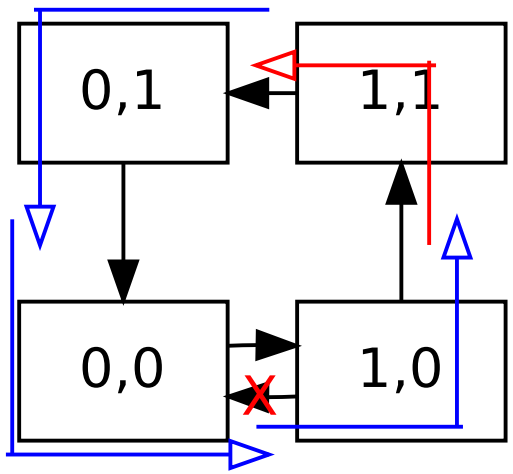
Two-by-Two Mesh Architecture

- 4 *nodes*
- each node with
  - 3 *arbiters* arb_*D*_*xy*
  - 3 *routers* r_*D*_*xy*
- *D*: direction (North, East, South, West, PE)
- *xy*: coordinates

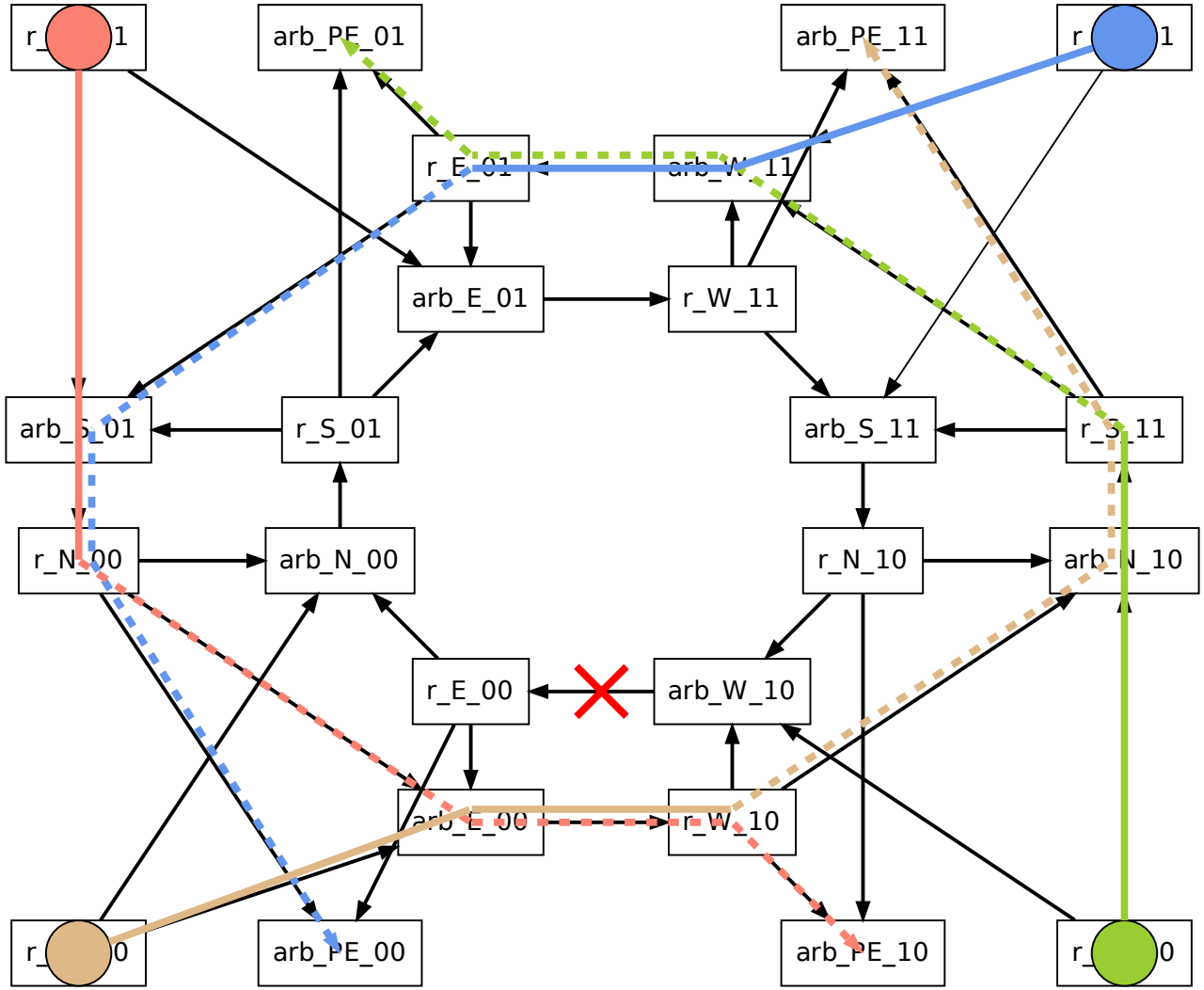


Principles of the Routing Algorithm

- Two-phase routing
  1. negative phase: towards south/west
  2. positive phase: towards north/east
- *Illegal turn*: switch from the positive phase back into the negative phase
- Tolerance of link faults: divert packets to take illegal turns
- Deadlock avoidance by dropping packets attempting illegal turns (if the path is occupied)



An Example of Cyclic Deadlock



link failure “arb_W_10 -> r_E_00” implies diversion & illegal turn for green packet from r_ip_10 to arb_ip_01

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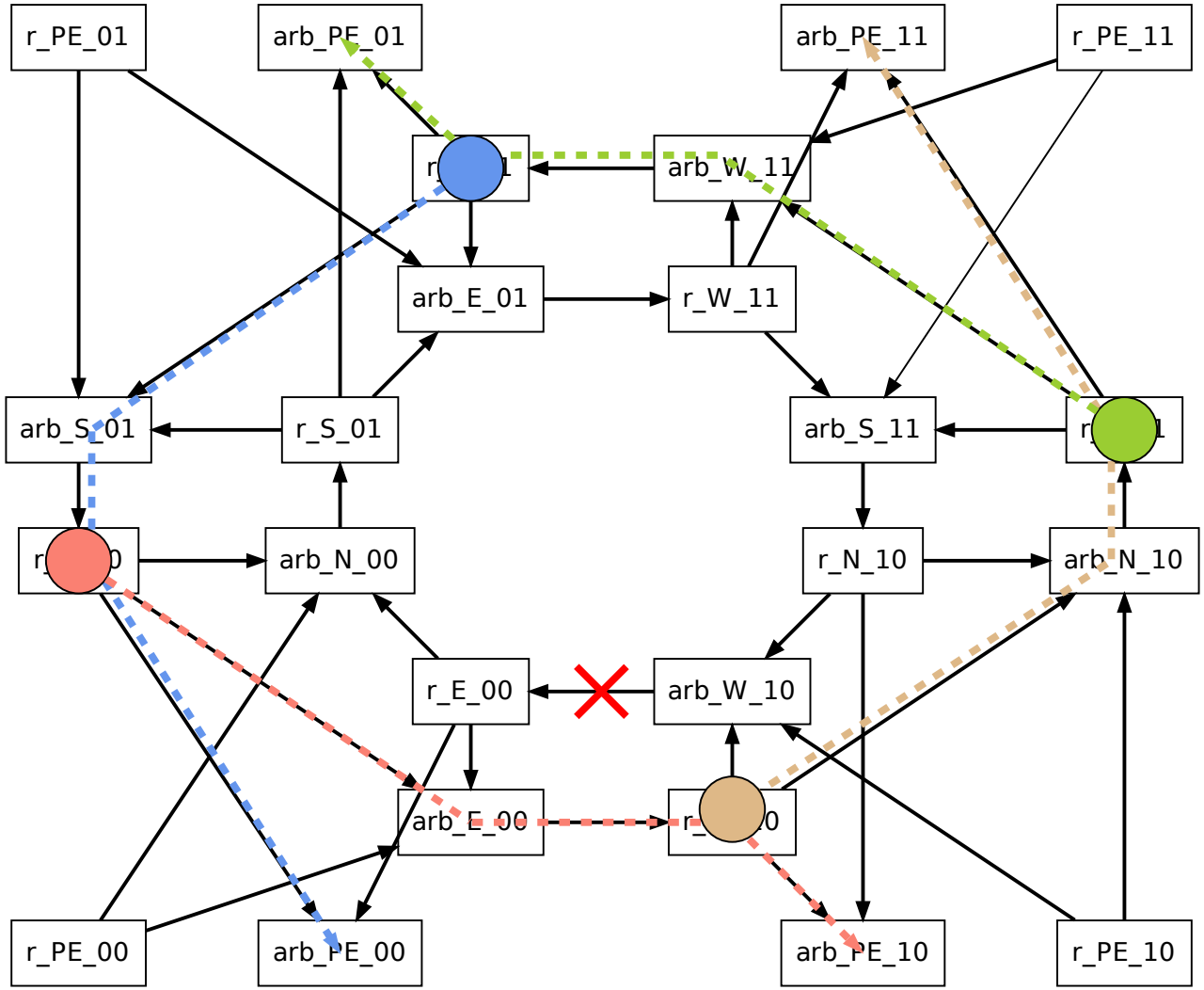

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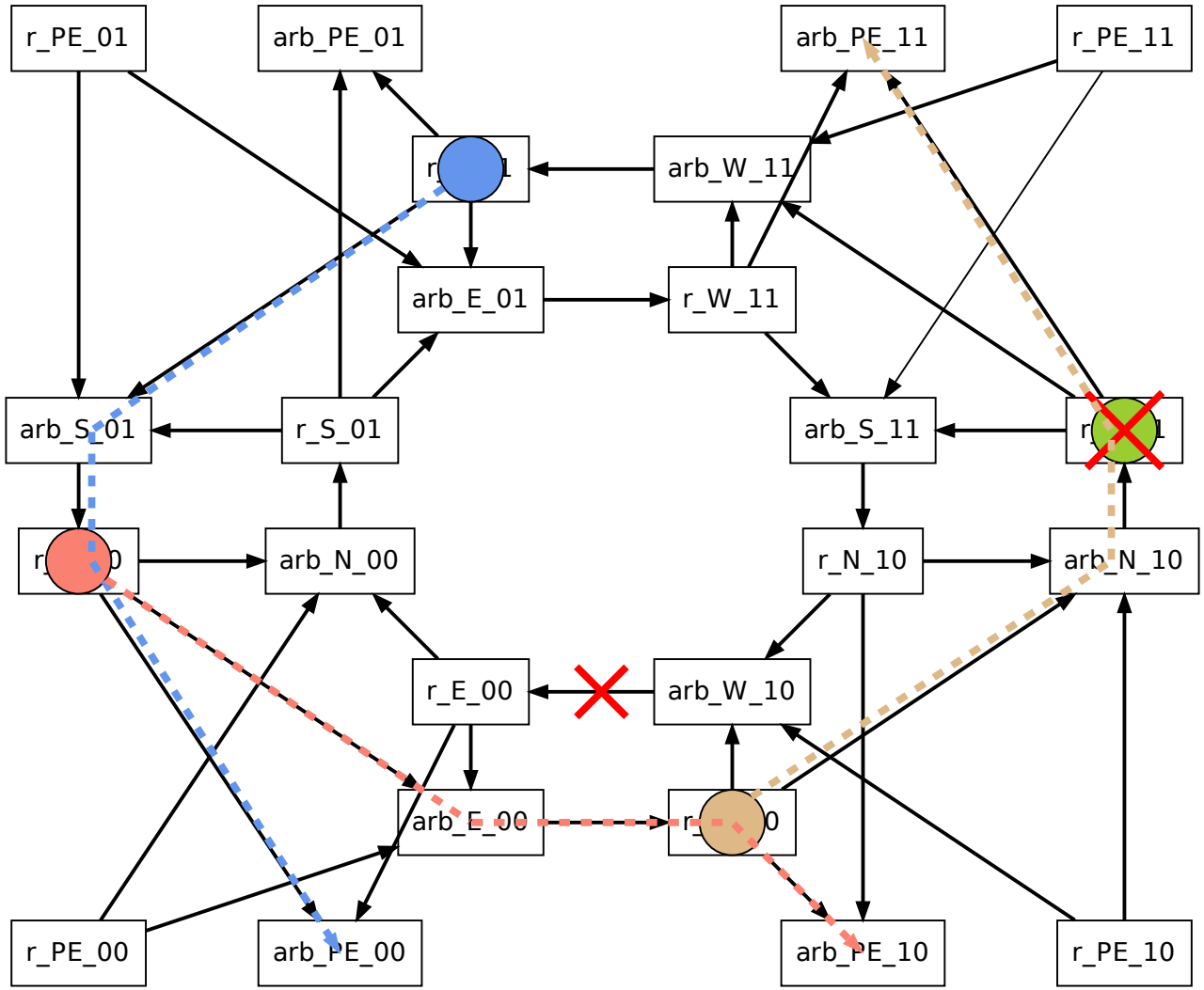
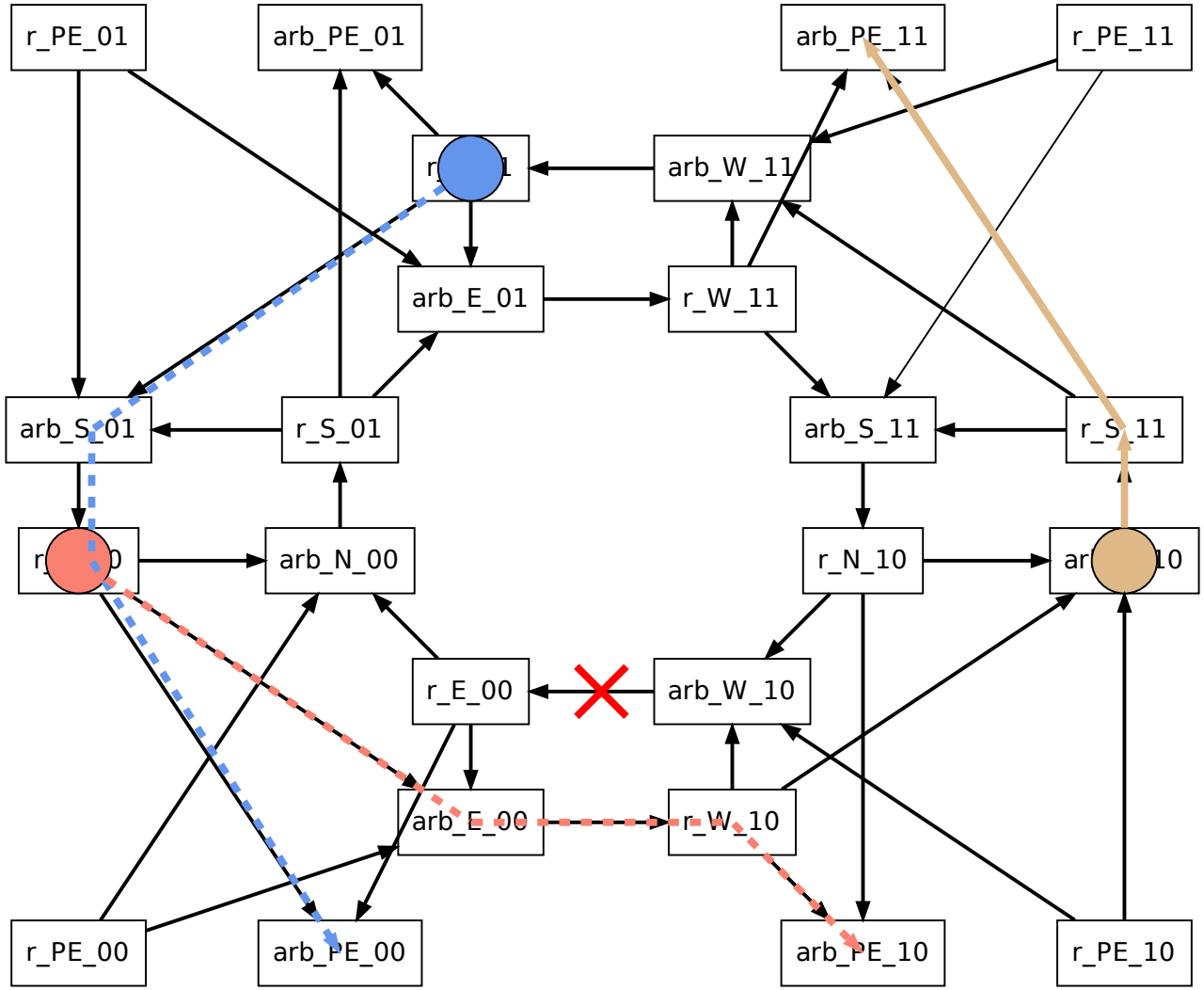
Deadlock Avoidance: Example

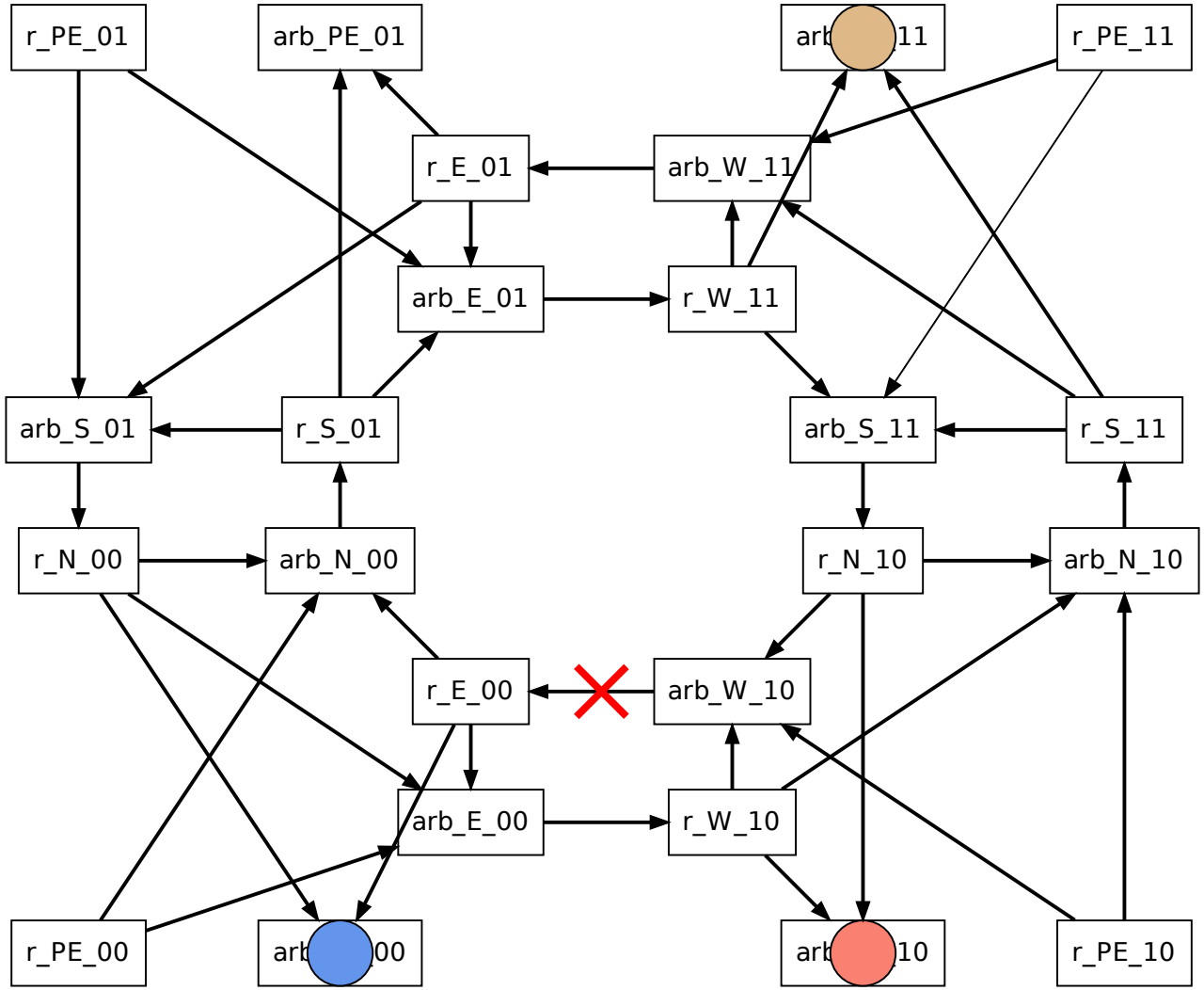


to avoid deadlock, drop green packet attempting an illegal turn

Deadlock Avoidance: Example



Deadlock Avoidance: Example



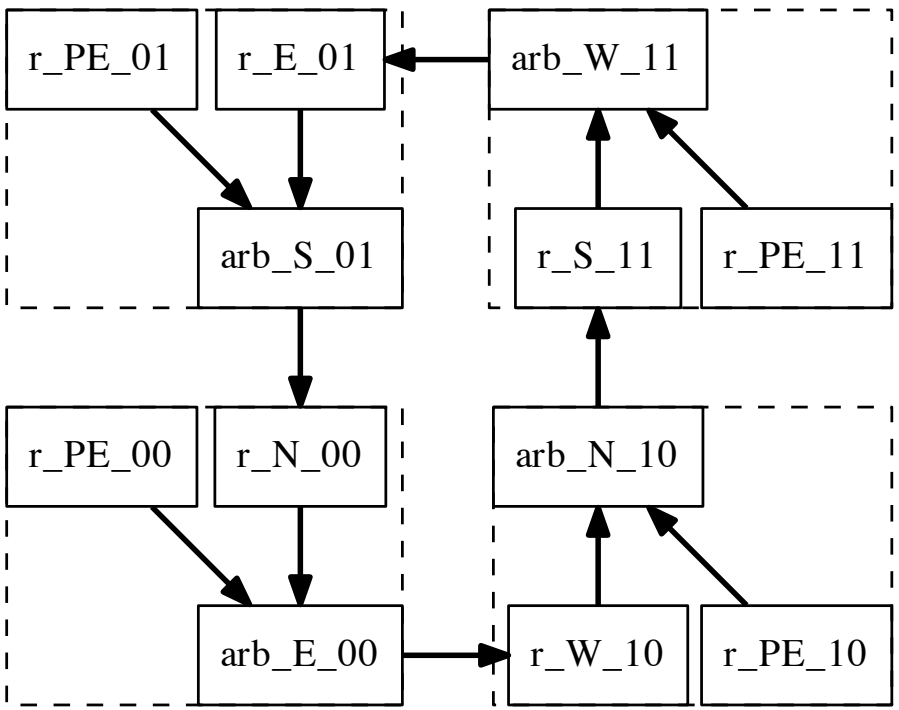
CADP (Construction and Analysis of Distributed Systems)

- Toolbox for the design of *asynchronous* systems
- Formal approach rooted in *concurrency theory*:
  process calculi, labeled transition systems, temporal logic
- Many verification techniques:
  simulation, model- and equivalence checking, compositional and distributed verification, test-case generation, performance evaluation, rapid prototyping
- Convenient languages for
  - system modeling (*LNT*),
  - temporal logic properties (*MCL*), and
  - execution of verification scenarios (*SVL*)
- More than 150 published case-studies and 70 third-party tools

For more information: `http://cadp.inria.fr`

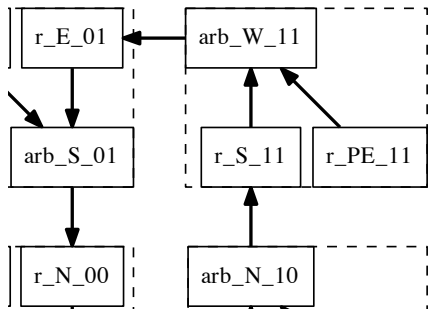
A Counterclockwise Routing Model

- Each PE router only generates one single-flit packet destined to the node in its diagonal direction.
- Only the counterclockwise routing direction is available.
  - No packet forwarding computation in the routers.
  - Packets take the north-west illegal turn in node (1,1).



LNT Model of the West Arbiter of Node (1,1) — arb_W_11

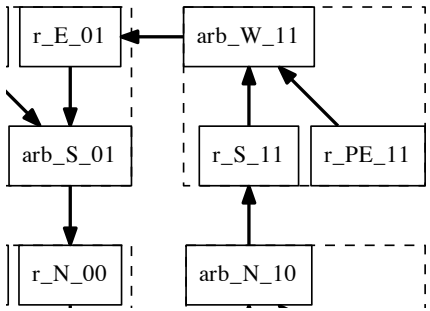
```
process arbiter_nack [ca, ra, ar : any] is
  loop
    var one_flit : Nat in
      select
        ar;                 -- Router r_E_01 is ready to accept packet
        select
          ca(?one_flit);    -- Receive packet from r_ip_11
          ar(one_flit)      -- Send packet to r_E_01
        []
          ra(true);         -- Ready to accept from r_S_11
          ra(?one_flit);    -- Receive packet from r_S_11
          ar(one_flit)      -- Send packet to r_E_01
        end select
      []
        ra(false)           -- Send negative acknowledgment to r_S_11
      end select
    end var
  end loop
end process

arbiter_nack [r_ip_11, r_S_11, r_E_01]   -- arb_W_11
```



LNT Model of the South Router of Node (1,1) — r_S_11

```
process router_drop_pkt [ar, ra : any] is
  loop
    var status : Bool, one_flit : Nat in
      ar;               -- Ready to accept packet from arb_N_10
      ar(?one_flit);    -- Receive packet from arb_N_10
      ra(?status);      -- Request arb_W_11's status
      if status then
        ra(one_flit)    -- Send packet to arb_W_11 ONLY on TRUE status
      end if
    end var
  end loop
end process
```

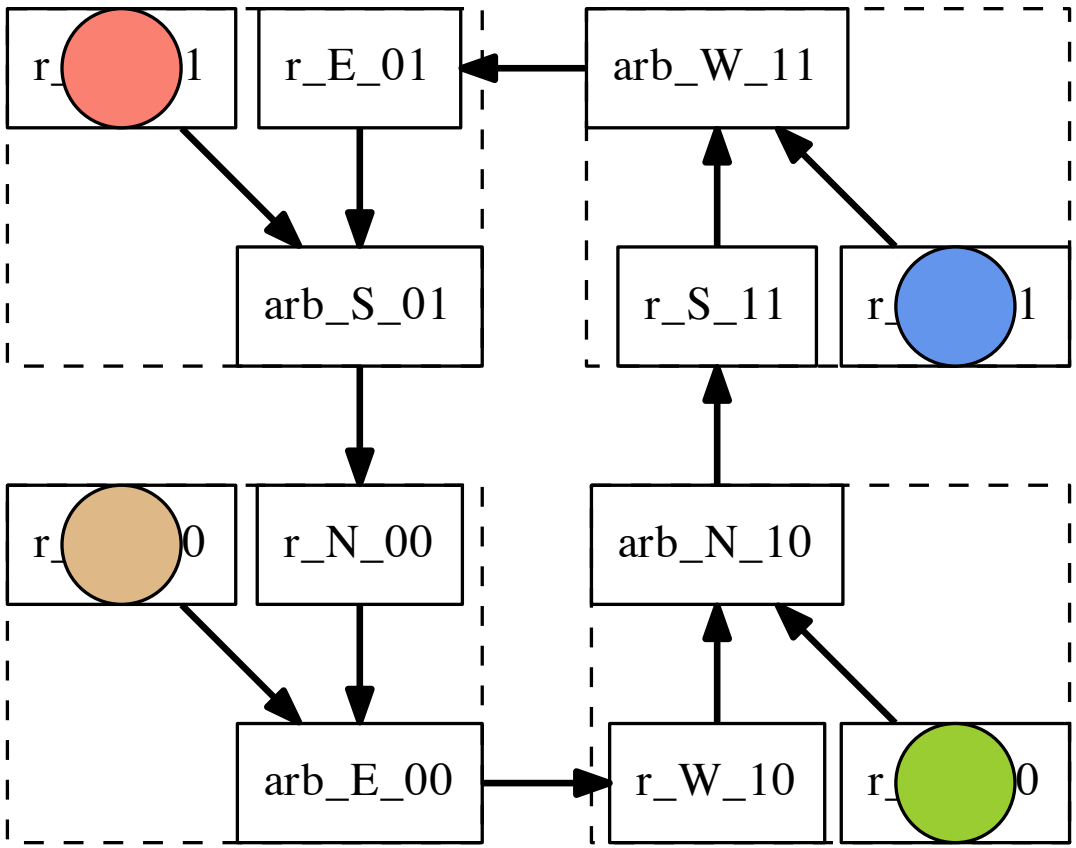
```
router_drop_pkt [arb_N_10, arb_W_11]   -- r_S_11
```



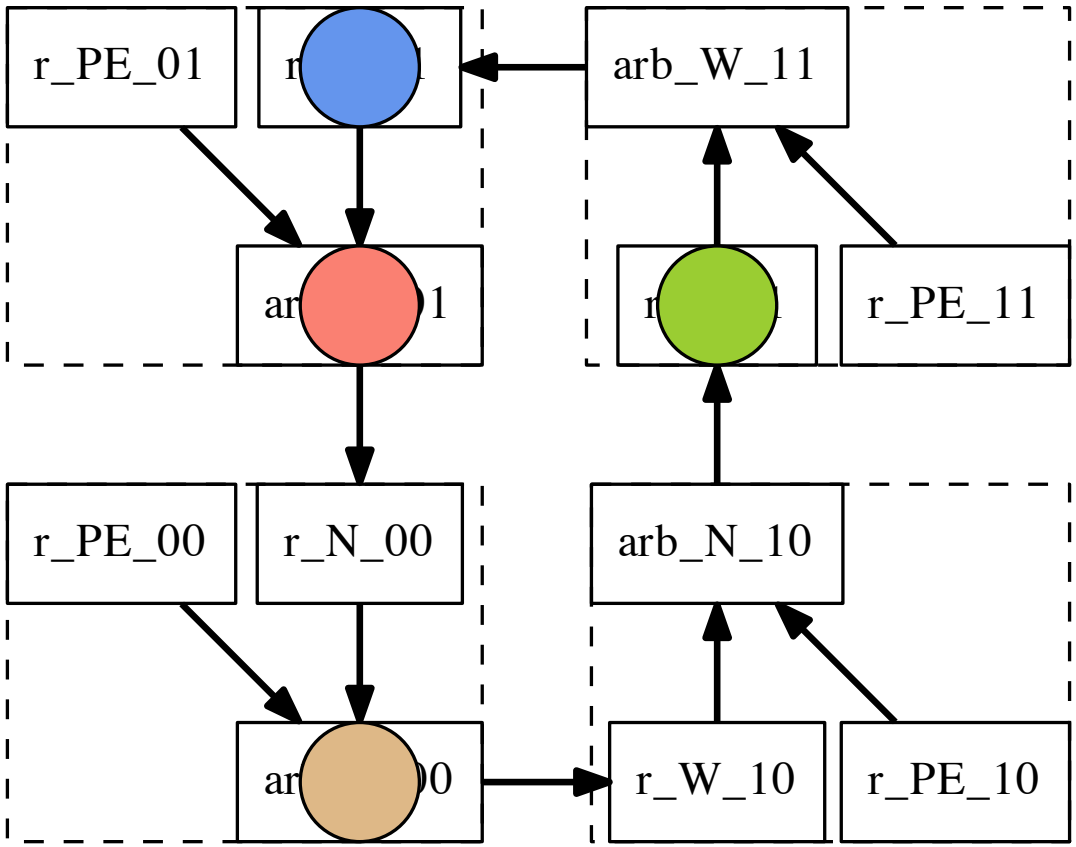
Verification Results for the Counterclockwise Routing Model

- No reduction techniques are required for state space generation.
- Deadlock avoidance mechanism drops packets making an illegal turn.
- Expected worst case:
  - three packets make illegal turns and get dropped;
  - at least one packet remains cycling in the network.
- *Reachability analysis finds deadlocks!*
- Diagnostic sequence (“packet leakage path”):
  All four packets get dropped due to deadlock avoidance.

Packet Leakage Transition Sequence



Packet Leakage Transition Sequence Example



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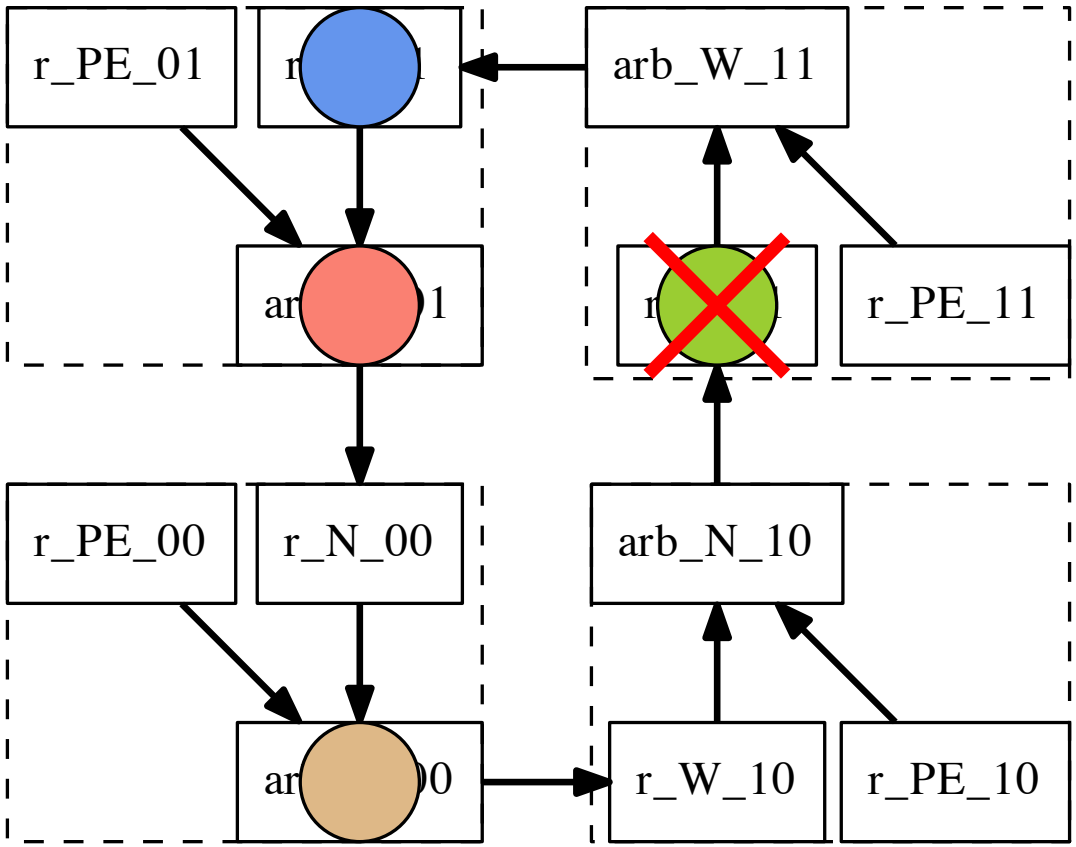

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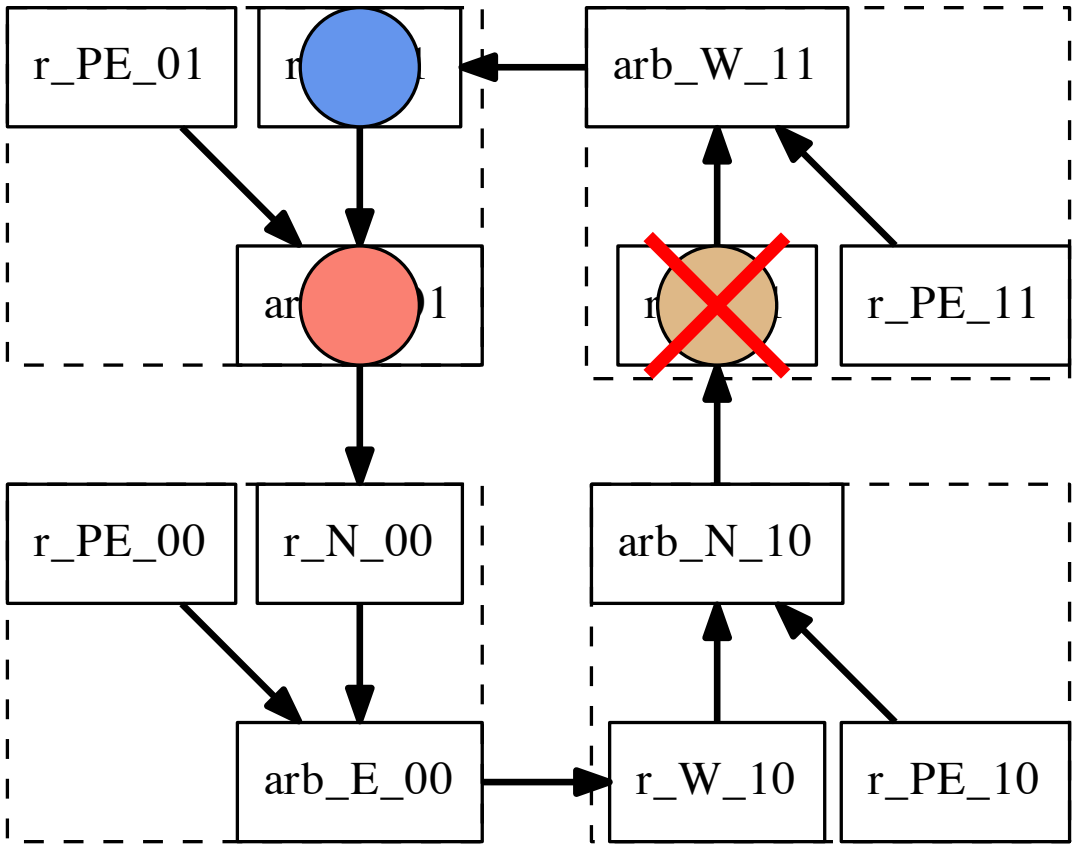

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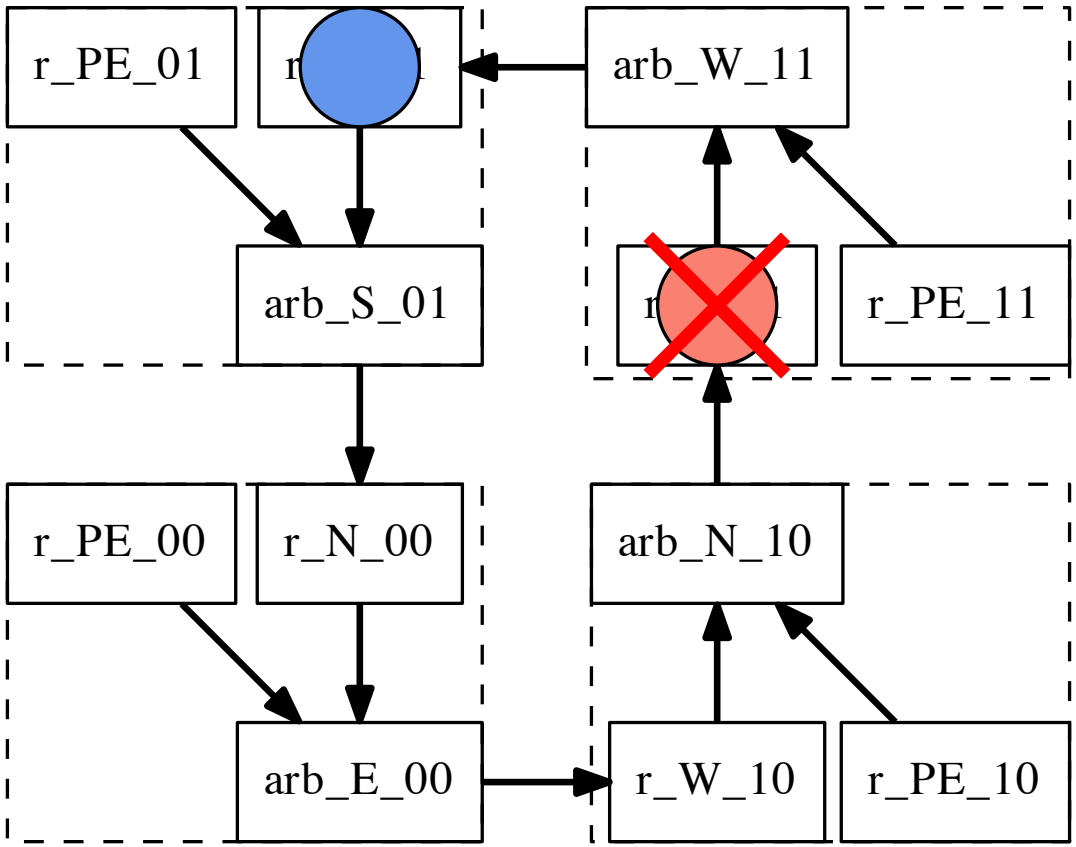

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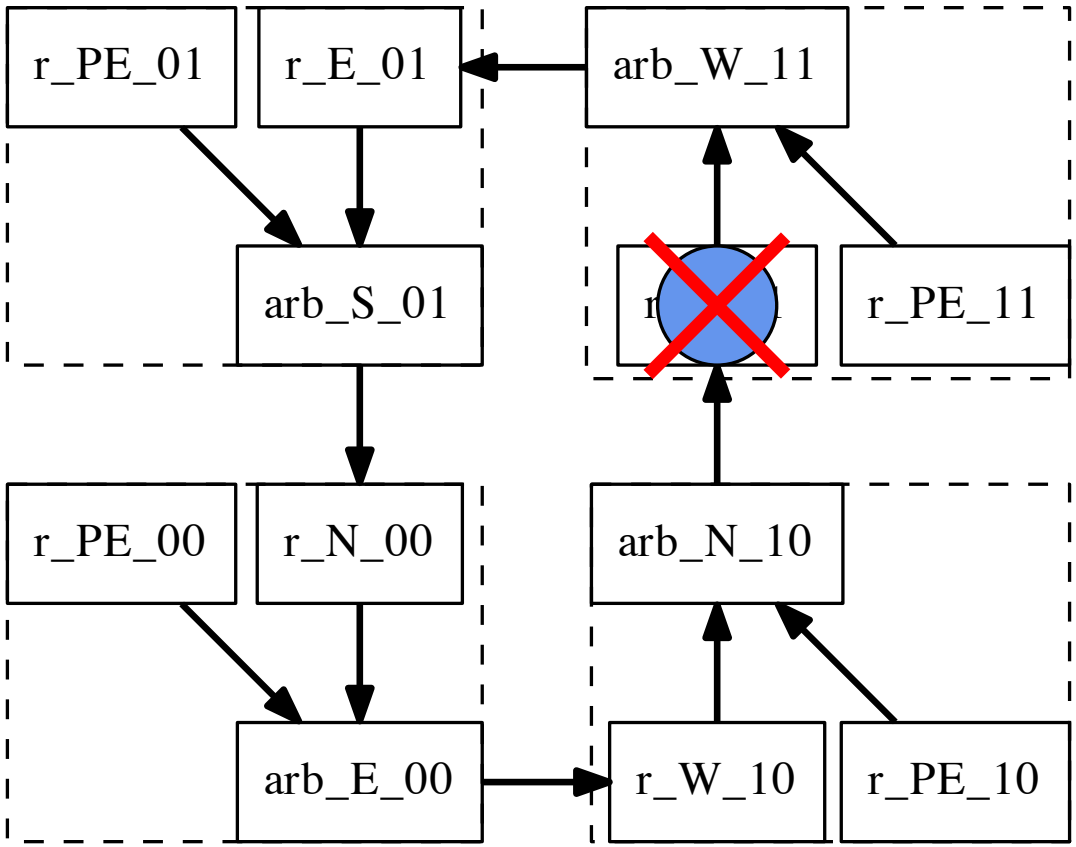
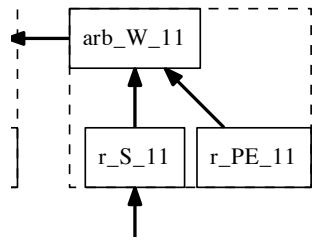


Reason for Packet Leakage in the West Arbiter of Node (1,1)

```
process arbiter_nack [ca, ra, ar : any] is
  loop
    var one_flit : Nat in
      select
        ar;                  -- Router r_E_01 is ready to accept packet
        select
          ca(?one_flit);     -- Receive packet from r_ip_11
          ar(one_flit)       -- Send packet to r_E_01
        []
          ra(true);          -- Ready to accept from r_S_11
          ra(?one_flit);     -- Receive packet from r_S_11
          ar(one_flit)       -- Send packet to r_E_01
        end select
      []
        ra(false)            -- Send negative acknowledgment to r_S_11
      end select
    end var
  end loop
end process

arbiter_nack [r_ip_11, r_S_11, r_E_01]   -- arb_W_11
```



Sending a negative acknoweldegment is *always* enabled!

Packet Leakage in the West Arbiter of Node (1,1)

- Arbiter arb_W_11: nondeterministic choice to send to r_S_11
  - a positive acknowledgement
  - a negative acknowledgement
- Negative acknowledgment always possible, regardless of potential deadlocks:
  a packet leakage path exists!

Possible solution: *prioritized choice: sending a positive acknowledgement with higher priority*

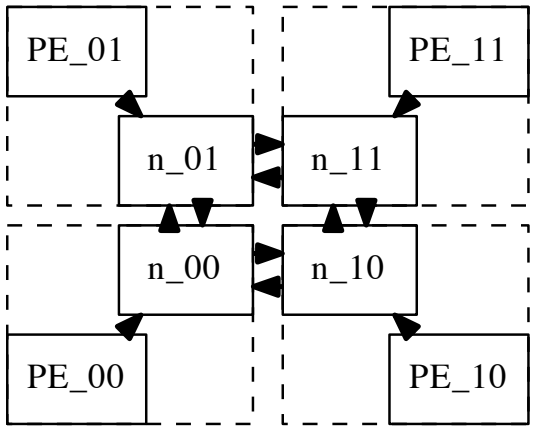
Drawbacks of the priority-based approach:

- LNT implementation of the priority choice requires additional processes, leading to possible state explosion.
- Pruning the unwanted execution paths from the generated state space using the priority operator in EXP.OPEN/SVL.
- The divergence-sensitive branching bisimulation is not a congruence for the priority operator.

Structural Abstraction to Reduce the State Space

- State explosion becomes a problem once all components are built for the two-by-two mesh.
- One major reason: interleavings of gate rendezvous between connected routers and arbiters.
- Idea: Merge routers and arbiters of one node into one process, completely removing rendezvous internal to a node.

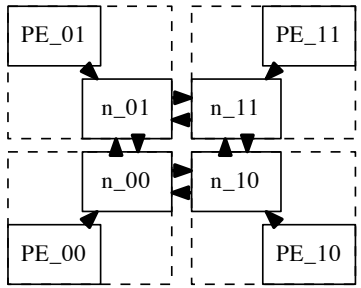
- Drawbacks of this simplification:
  - It removes the possibility of multiple packets passing through a single node at the same time.
  - It removes the buffering capacity of each arbiter, which *causes deadlock*.



Example of Deadlock

```
process n00 [ip_00, ...] is
  loop
    var one_flit : Nat in
      select
          ip_00(?one_flit);
          if one_flit == 1 then
            n00_n01(one_flit)
          else
             ...
          end if
      []
          n01_n00(?one_flit);
          ...
      []
          n10_n00(?one_flit);
          ...
      end select
    end var
  end loop
end process
```

```
process n01 [ip_01, ...] is
  loop
    var one_flit : Nat in
      select
          ip_01(?one_flit);
          if one_flit == 0 then
            n01_n00(one_flit)
          else
           ...
          end if
      []
          n00_n01(?one_flit);
          ...
      []
          n11_n01(?one_flit);
          ...
      end select
    end var
  end loop
end process
```



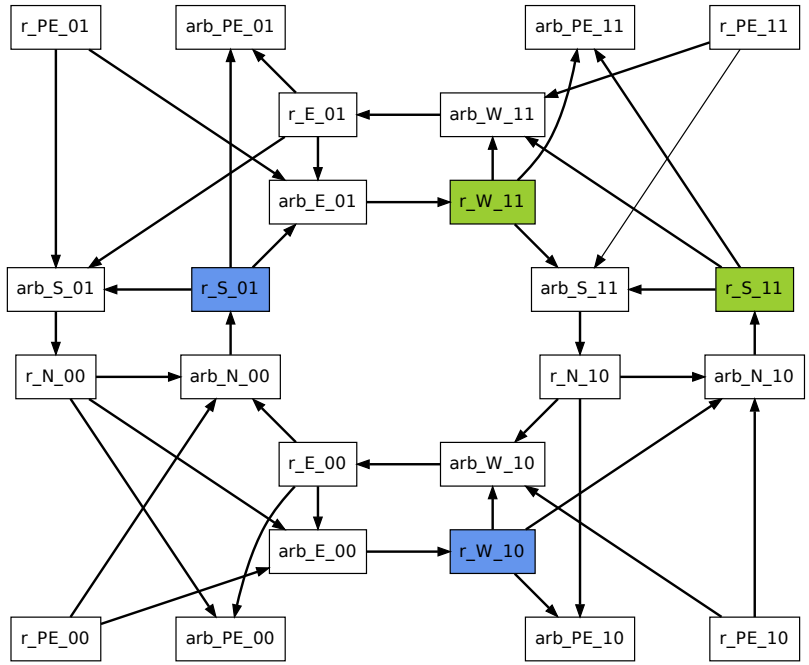

```
par
    n00_n01, n01_n00, ... -> n00 [...]
|| n00_n01, n01_n00, ... -> n01 [...]
end par
```

Finding Proper Data Abstractions

- The counter-clockwise routing experiment reveals the packet leakage in certain arbiter's design.
- The experiment with bufferless arbiters shows the necessity of arbiter's buffering ability.
- Data abstraction is required to keep the state space manageable.
- The packet's content is *only* checked by routers to precisely determine the next forwarding direction.
- Each router may potentially send a randomly destined packet to any possible forwarding direction.
- Abstract the precise forwarding direction decision with *nondeterministic choice*.
- This abstraction results in manageable state space.

Finding Proper Data Abstractions

- Constraints:
  - Fault-tolerance provides alternative route(s) for all packets.
  - Router's nondeterministic choice should allow all forwarding directions for a randomly destined packet.
  - Illegal turns are never the preferred choice unless all forwarding routes of a router are illegal.
- Routers are classified into three types:
  - RI2 can make only one illegal turn: r_S_11 and r_W_11;
  - RI1 can make one illegal turn and one legal turn: r_W_10 and r_S_01;
  - RI0 makes no illegal turn: all other routers.



Packets Without Data

- Extreme abstraction: eliminate the packet entirely, use pure synchronization
- The packet leakage still exists at RI2 (router allowing only illegal turns):
  - RI2 has two choices for a packet: to drop it or forward it on an illegal turn.
  - With no packet content, the nondeterministic choice may always take the illegal turn.
  - An illegal turn leads to packet drop regardless of deadlock avoidance.
- A packet takes an illegal turn *only* after an unsuccessful attempt to take route due to a failure on the route.
- Stated otherwise: When a packet makes an illegal turn, it must have been diverted at least once before.
- Use a single-bit Boolean variable to model packet data: true iff packet has been diverted before.

The LNT Process for RI2

```
process router_two_illegal [input, out_arb_ip, out1_illegal,
                            out2_illegal, drop : any] is
  var one_flit, arb_status : Bool in loop
    input(?one_flit);
    select
      out_arb_ip(one_flit)
    []
      if one_flit == true then
        -- priority to out1_illegal
        out1_illegal(?arb_status);
        if arb_status == true then out1_illegal(one_flit)
        else
          out2_illegal(?arb_status);
          if arb_status == true then out2_illegal(one_flit)
          else drop -- both illegal turns impossible
          end if
        end if
      else stop end if
    end select
  end loop end var
end process
```

The LNT Process for The Arbiter Corresponding to RI2

```
process arbiter_nack_2 [in_ip_router, in1_illegal,
                        in2_illegal, arb_out : any] is
var one_flit : Bool in
   loop select
      in_ip_router(true); in_ip_router(?one_flit);
      loop L1 in select
         arb_out(one_flit); break L1
      [] in1_illegal(false)
      [] in2_illegal(false)
      end select end loop -- L1
   [] in1_illegal(true); in1_illegal(?one_flit);
      loop L2 in select
         arb_out(one_flit); break L2
      [] in1_illegal(false)
      [] in2_illegal(false)
      end select end loop -- L2
   [] in2_illegal(true); in2_illegal(?one_flit);
      loop L3 in select
         arb_out(one_flit); break L3
      [] in1_illegal(false)
      [] in2_illegal(false)
      end select end loop -- L3
   end select end loop
end var end process -- arbiter_nack_2
```

Compositional LTS generation for Two-by-Two NoCs

- Nine scenarios: without failed link plus all possible single link failures
- SVL scripts to automate compositional LTS generation and reduction
- No deadlocks found in any of the generated LTSs
- All but route-failure and drop gates hidden:
  - No route failures: no corresponding label in the LTSs
  - No packet drop for a single packet in the NoC
  - Packet drop possible whenever more than one packet in the NoC

Failure	Interm. LTS Size		Final LTS		Performance		Labels
Link	States	Transitions	St.	Tr.	RAM	Time	
none	6,295,773	83,386,208	1	1	32,945	5,976	i
01 $\rightarrow$ 00	20,340	193,726	41	224	111	83	i, drop_Sr_11, drop_Wr_11
01 $\rightarrow$ 11	1,369,068	18,221,153	1	3	4,039	499	i, drop_Sr_01, drop_Sr_11
00 $\rightarrow$ 10	6,560	50,688	21	104	111	80	i, drop_Sr_11, drop_Wr_11
00 $\rightarrow$ 01	6,560	50,688	21	104	111	81	i, drop_Wr_11, drop_Sr_11
10 $\rightarrow$ 11	122,724	1,269,981	1	3	111	89	i, drop_Wr_10, drop_Wr_11
10 $\rightarrow$ 00	20,340	193,726	41	224	111	80	i, drop_Wr_11, drop_Sr_11
11 $\rightarrow$ 01	367,200	4,172,652	1	3	111	106	i, drop_Sr_11, drop_Wr_11
11 $\rightarrow$ 10	367,200	4,172,652	1	3	111	105	i, drop_Sr_11, drop_Wr_11

Conclusion & Future Work

- Formal Analysis facilitates detection of design flaws (packet leakage)
- Gain deeper understanding of the routing algorithm (necessary buffering capacity of the arbiters)

- Extension of the LNT model to larger networks (three-by-three, four-by-four, ...), where nodes differ in the number of connections
- Study packet delivery guarantees
- Refine abstractions
- Can the discovered symmetries help in fighting the state space explosion?
- Enrich the model to enable performance analysis