






# Deadlock Recovery in Asynchronous Networks on Chip in the Presence of Transient Faults

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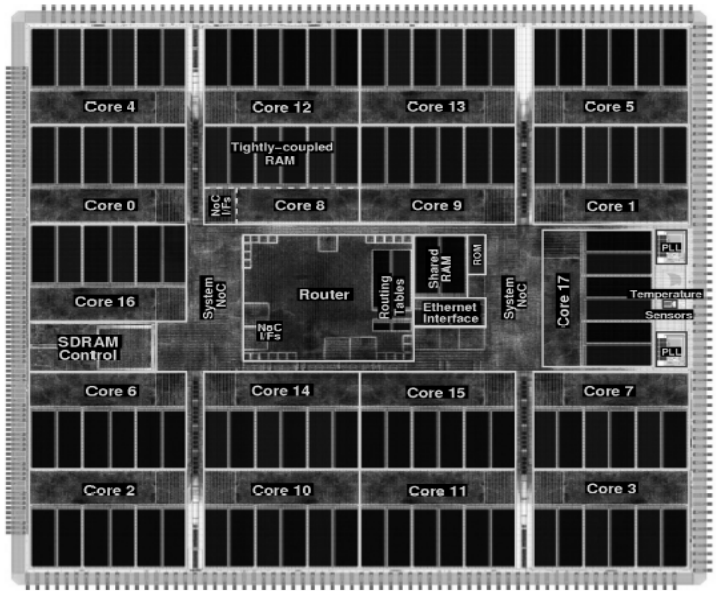
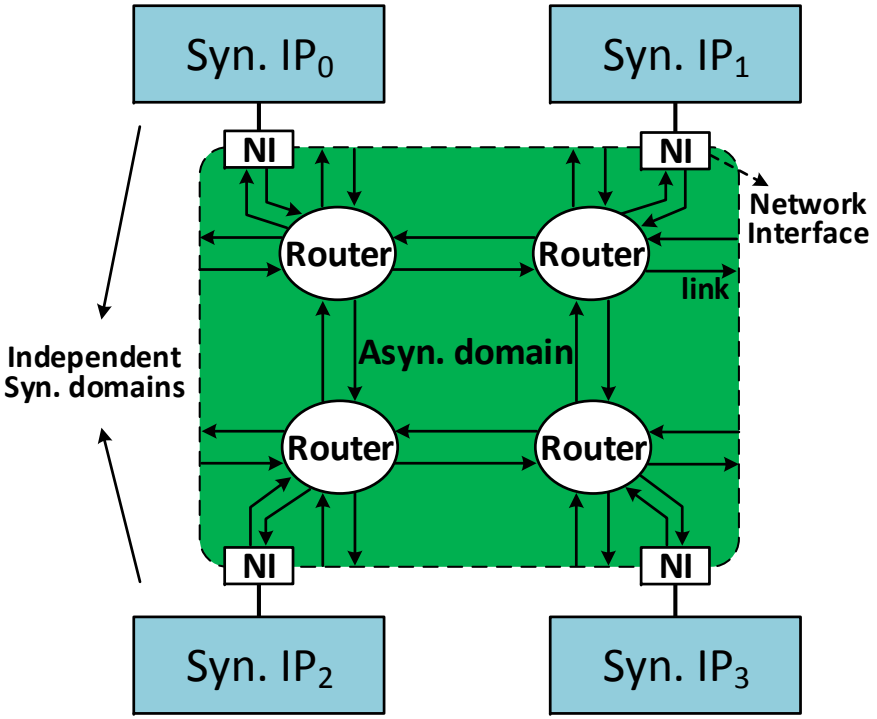
# Asynchronous Networks on Chip (NoCs)

1. **Multi-core era --- Network-on-chip (NoC)**
2. **Asynchronous Networks on Chip --- GALS system**




**SpiNNaker** MPSoC with 18 ARM cores




A GALS system constructed by an asynchronous NoC

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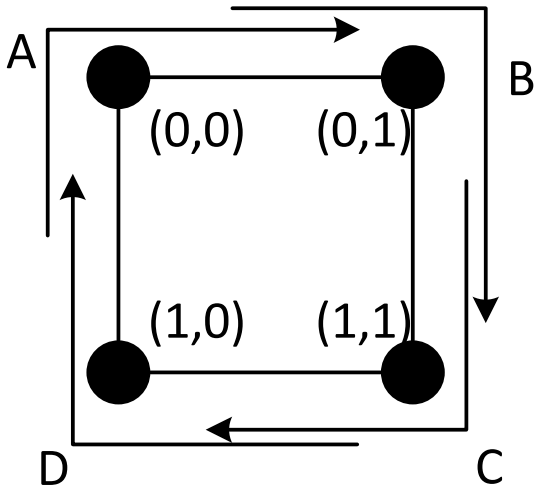
# Deadlock in synchronous NoCs

## 1. Traditional deadlock: cyclic dependence




**2. Deadlock avoidance:** turn models, virtual channels

**3. Deadlock recovery:** deadlock or congestion?

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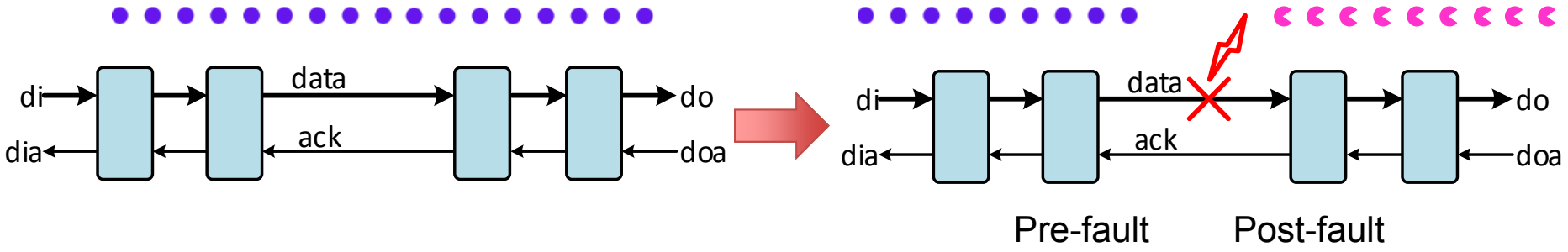
# Deadlock in asynchronous NoCs

1. **Traditional deadlock**
2. **Permanent faults***

Deadlocked QDI pipeline caused by permanent faults:




**Transient faults?**

*G. Zhang, etc., “An asynchronous SDM network-on-chip tolerating permanent faults,” ASYNC 2014

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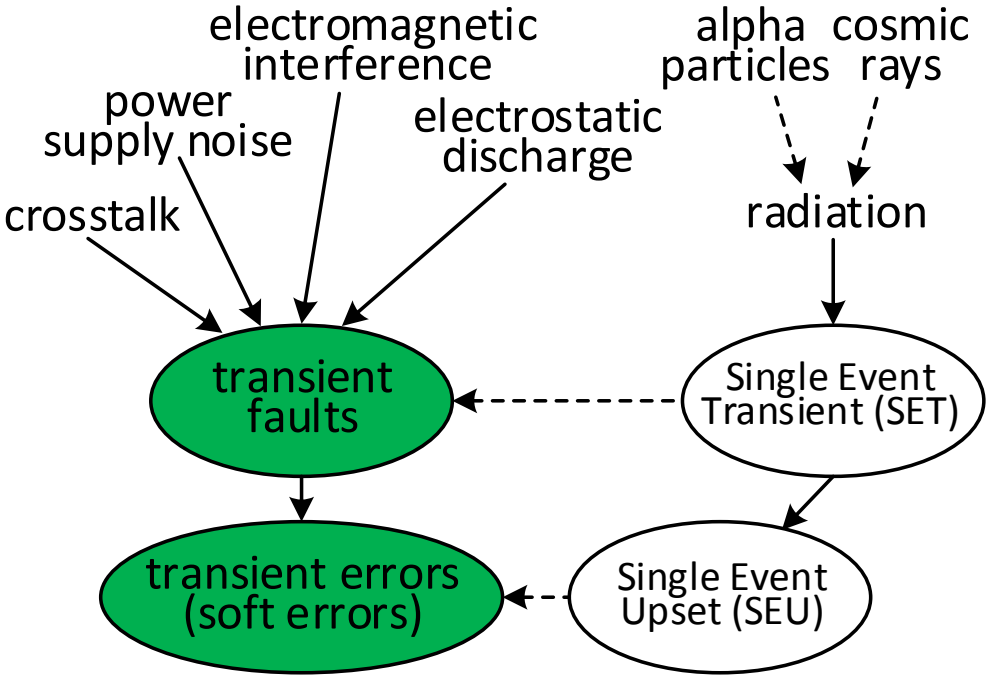
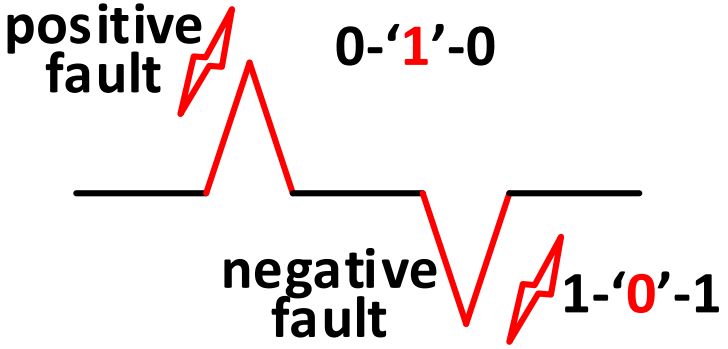
# Transient faults




Sources of Transient faults




Positive/negative

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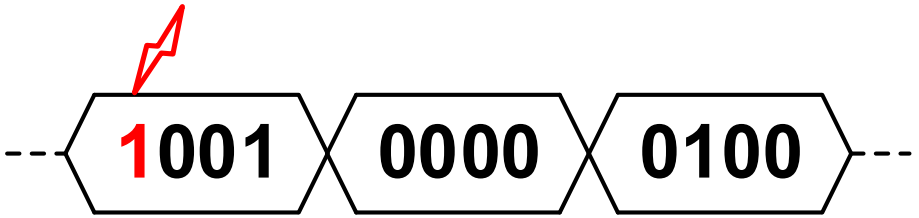
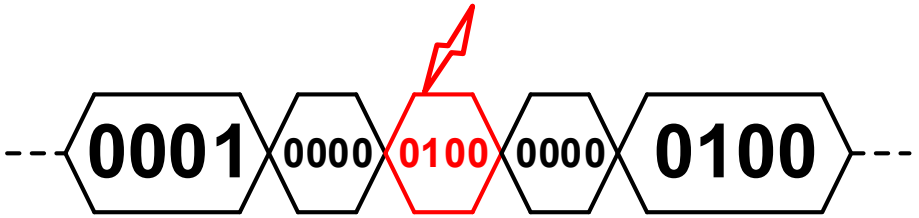
# Impact of transient faults on QDI pipelines
(4-phase 1-of-4 pipeline)

1. Symbol corruption*




2. Symbol insertion*




3. **Deadlock ?**

*G. Zhang, etc, “Protecting QDI interconnects from transient faults using delay-insensitive redundant check codes,” Microprocessors and Microsystems, 2014

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# Why this work is important?

**Deadlock ?**

- Usual network deadlock (network/data link layer)
- Congestion
- Deadlock due to permanent faults (physical layer)
- Deadlock due to transient faults (physical layer)

1. Differentiate all deadlock types
2. All deadlock detection could use a common time-out mechanism
3. A fine-grained recovery mechanism (system reboot? NO!!!)

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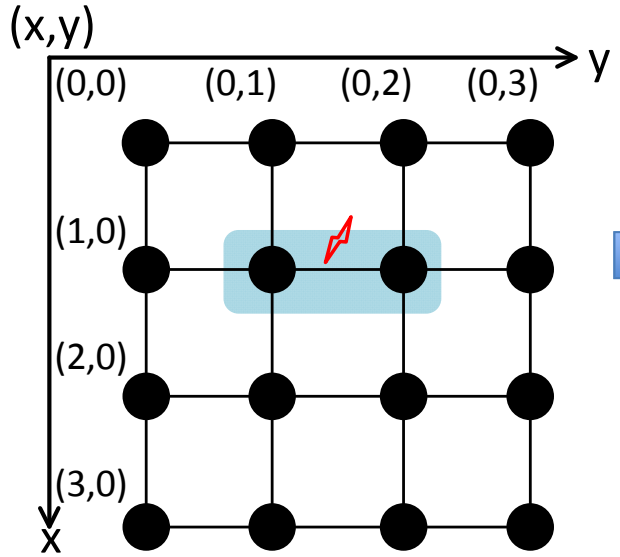
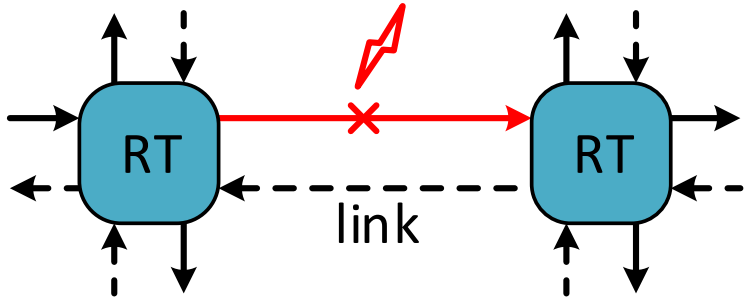
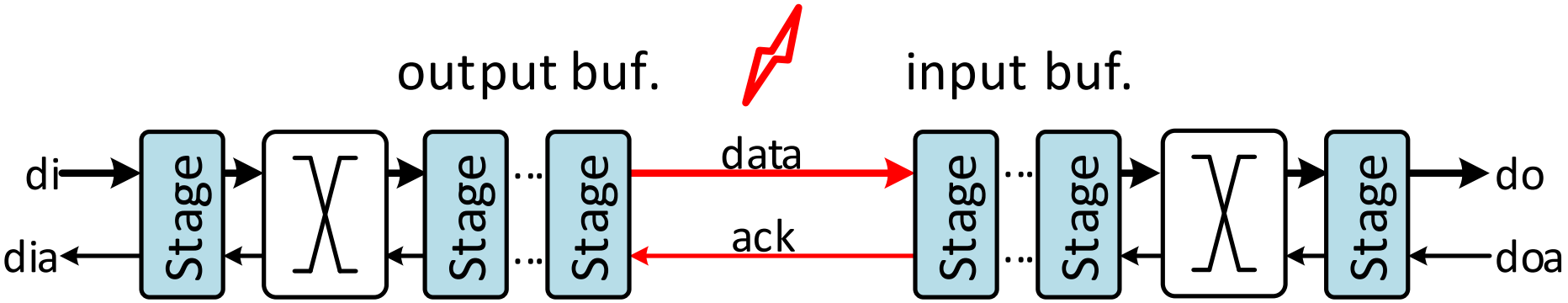
# Modelling QDI Asynchronous NoCs



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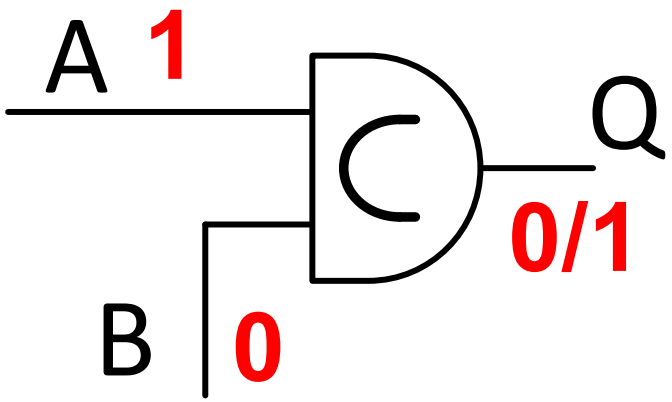
# Deadlocked QDI pipeline

***Deadlock*: In a deadlocked QDI pipeline, no transitions could be fired any more and the pipeline gets stuck at a "stable" state.**




$$A \wedge B \rightarrow Q\uparrow$$
$$\neg A \wedge \neg B \rightarrow Q\downarrow$$

Deadlock state: ( A==1, B==0)  or (A==0, B==1)

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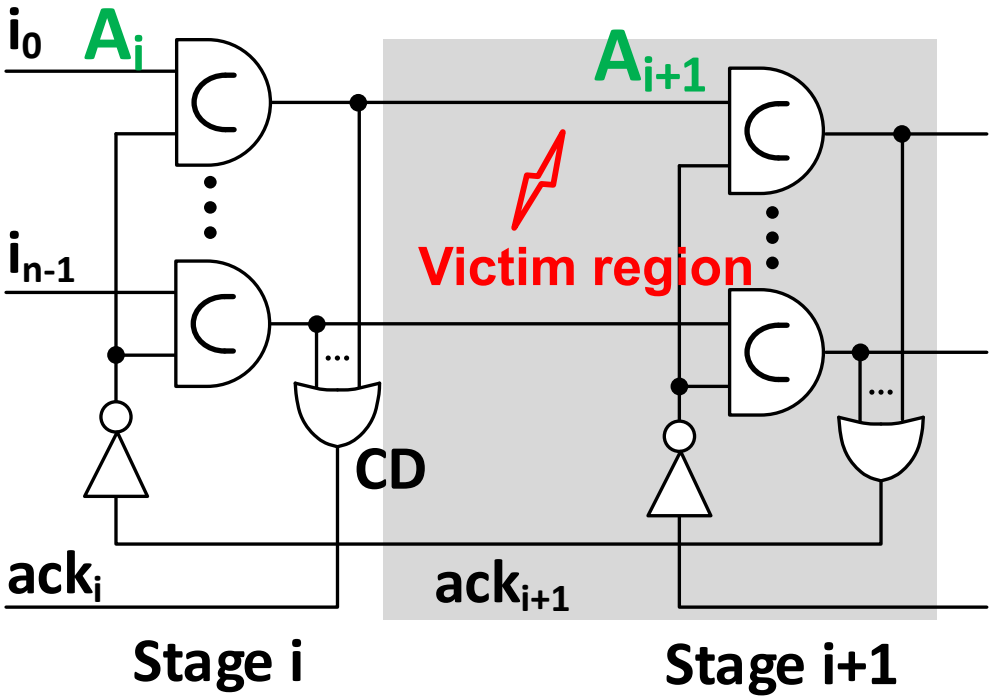
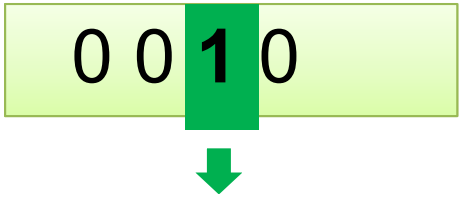
# Single-word 4-phase 1-of-n pipeline




1-of-4 word:




Active wire (A)

Theorem 1: A transient fault can cause symbol corruption and insertion, but **NOT** deadlock.

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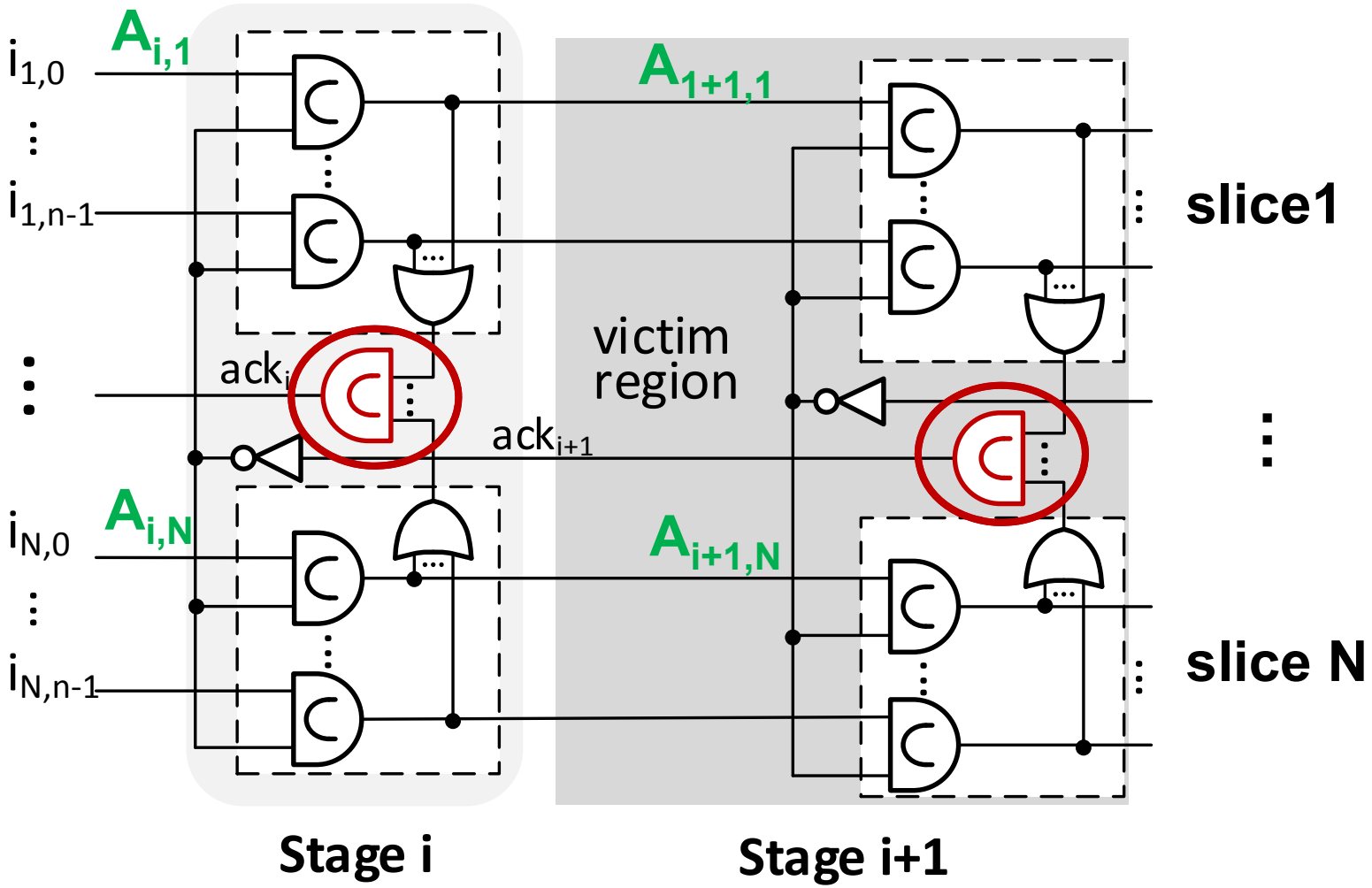
# Deadlock of a multi-word pipeline



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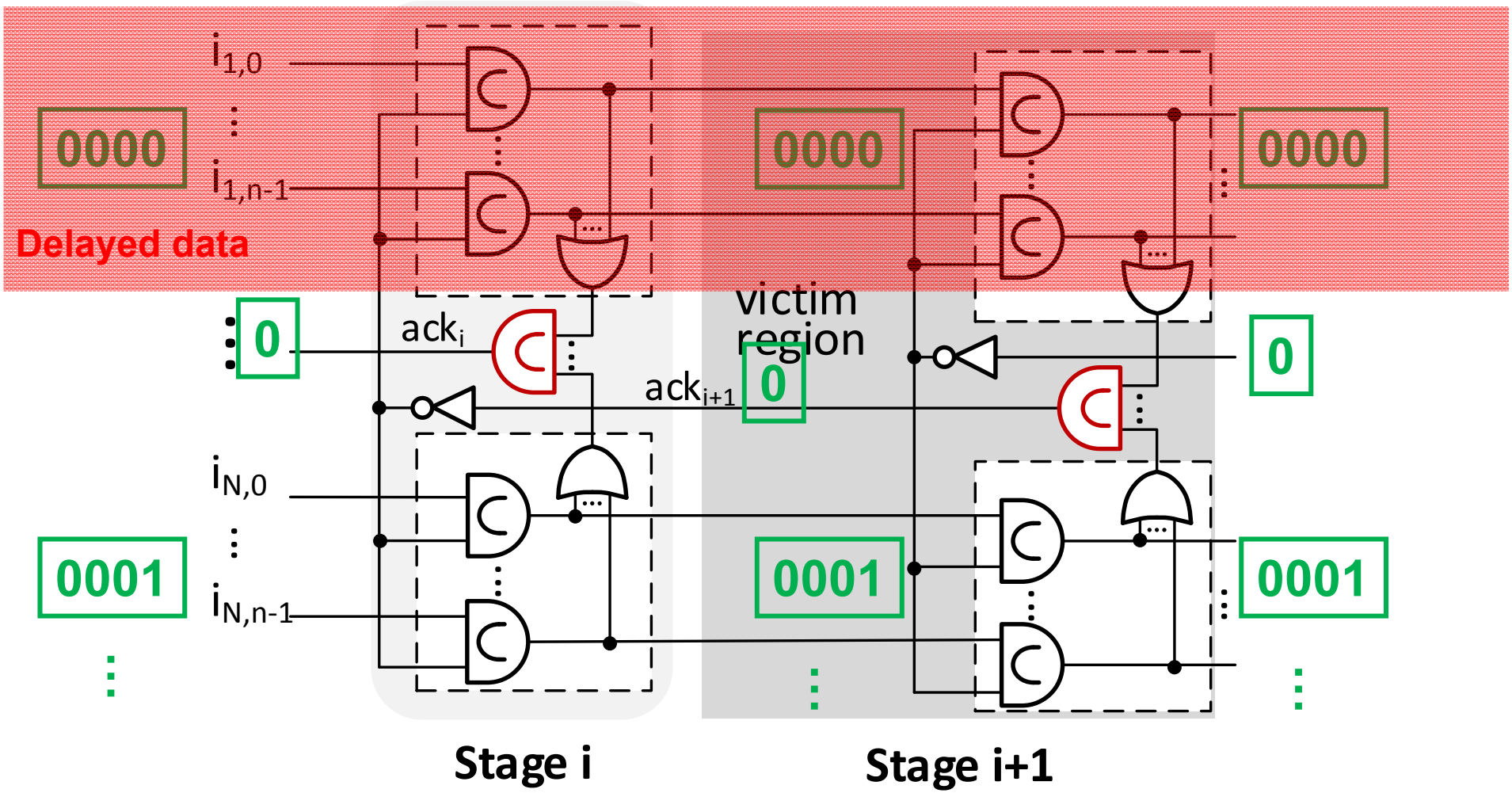
# Deadlock of a multi-word pipeline (1/7)



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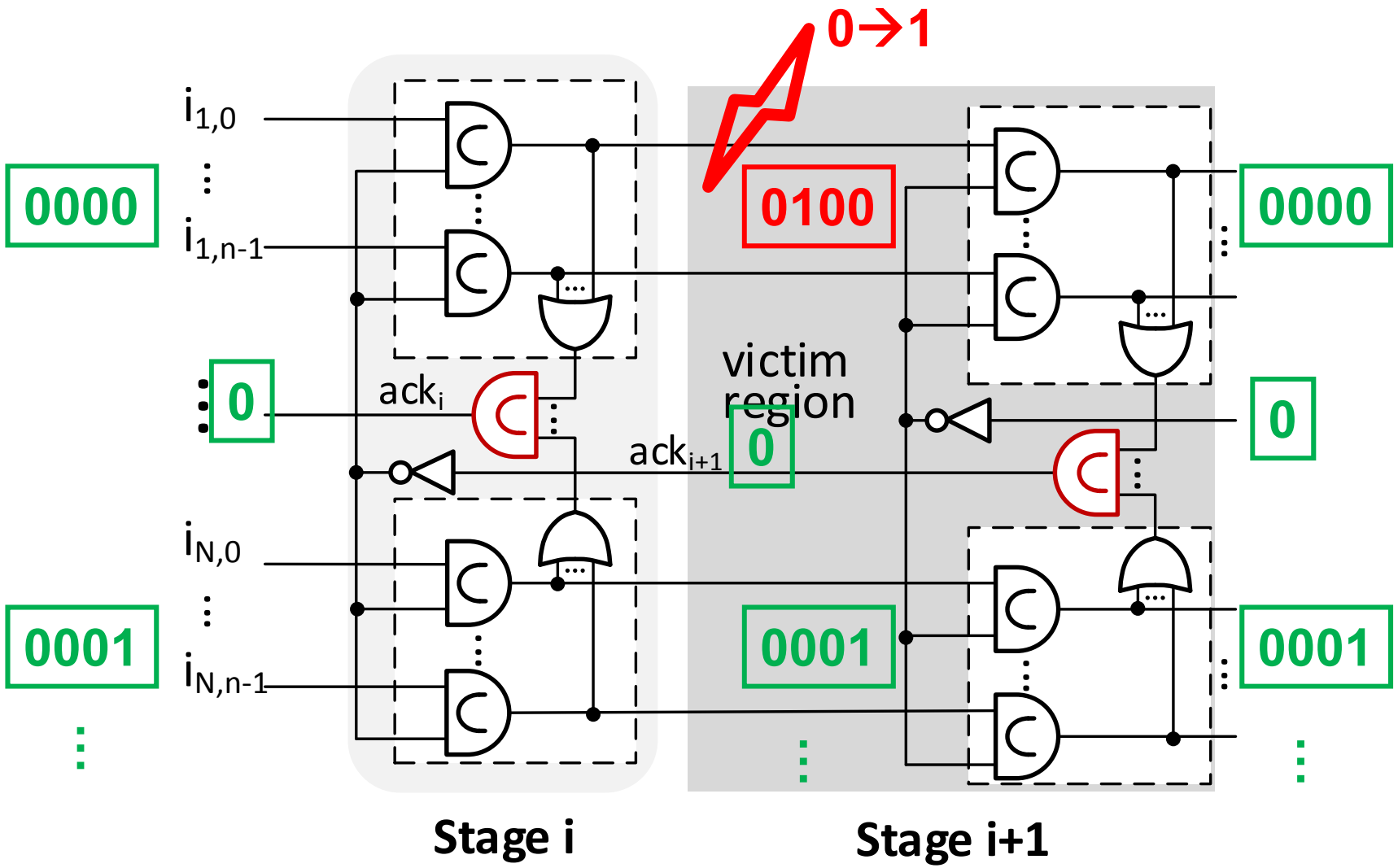
# Deadlock of a multi-word pipeline (2/7)



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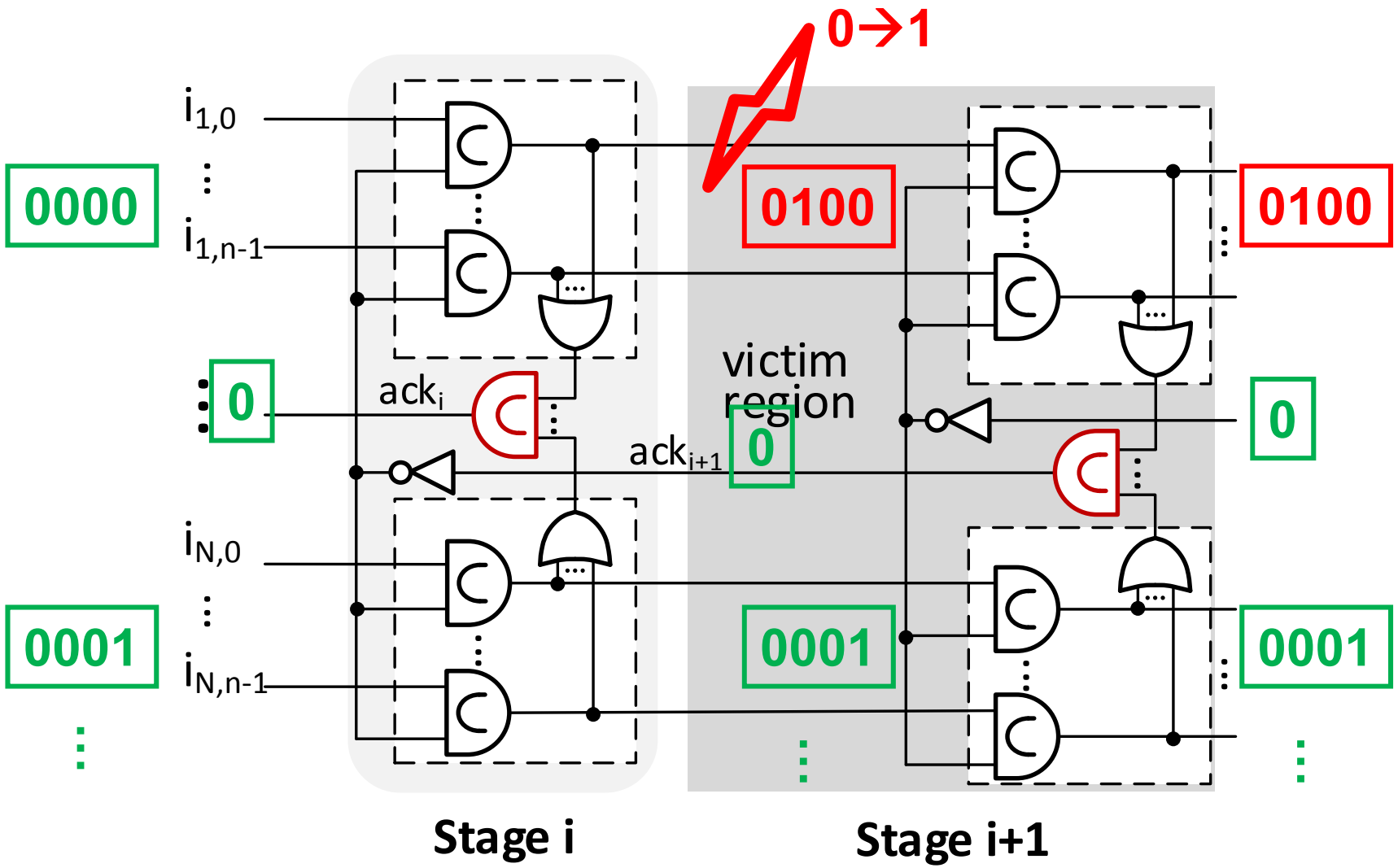
# Deadlock of a multi-word pipeline (3/7)



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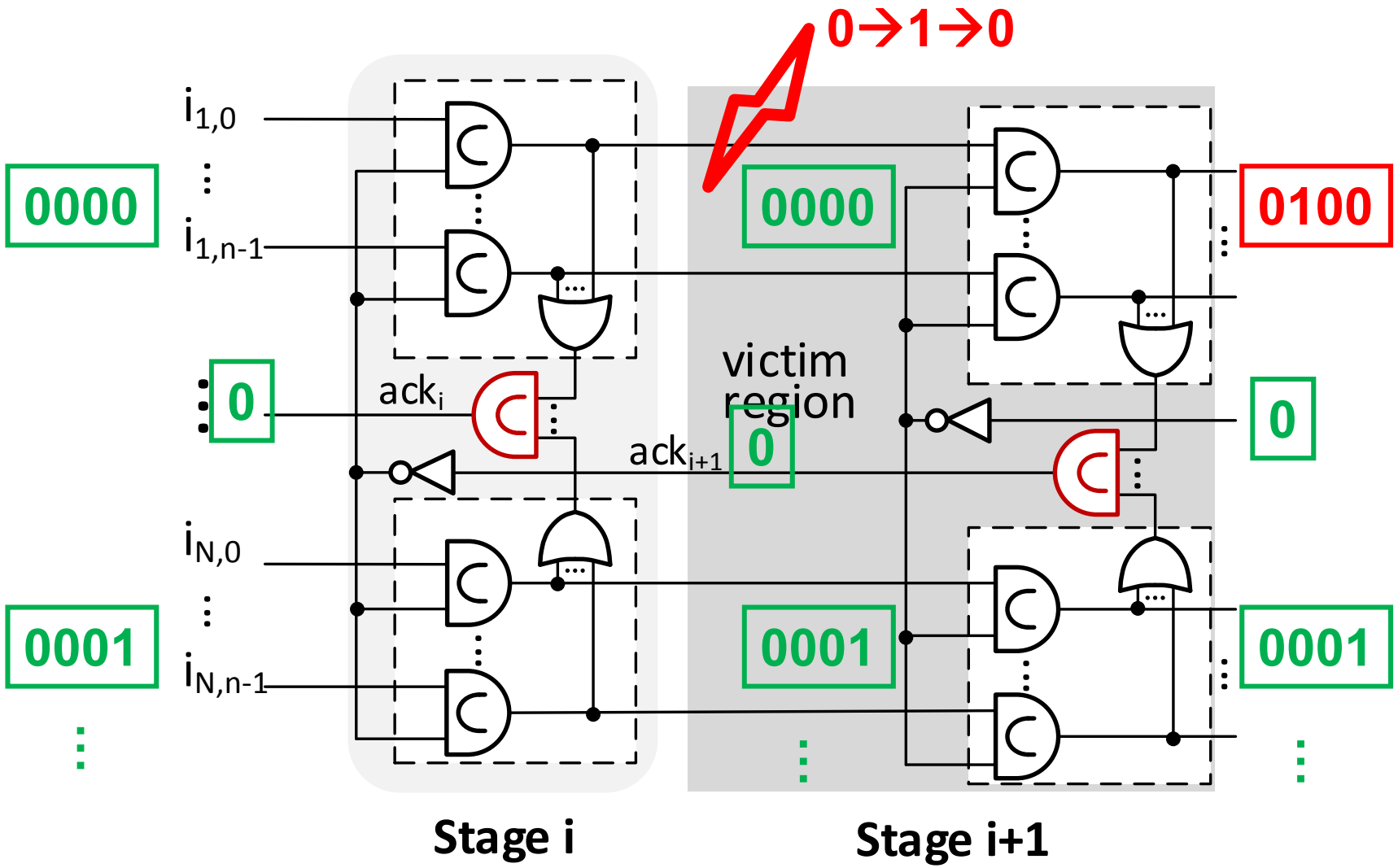
# Deadlock of a multi-word pipeline (4/7)



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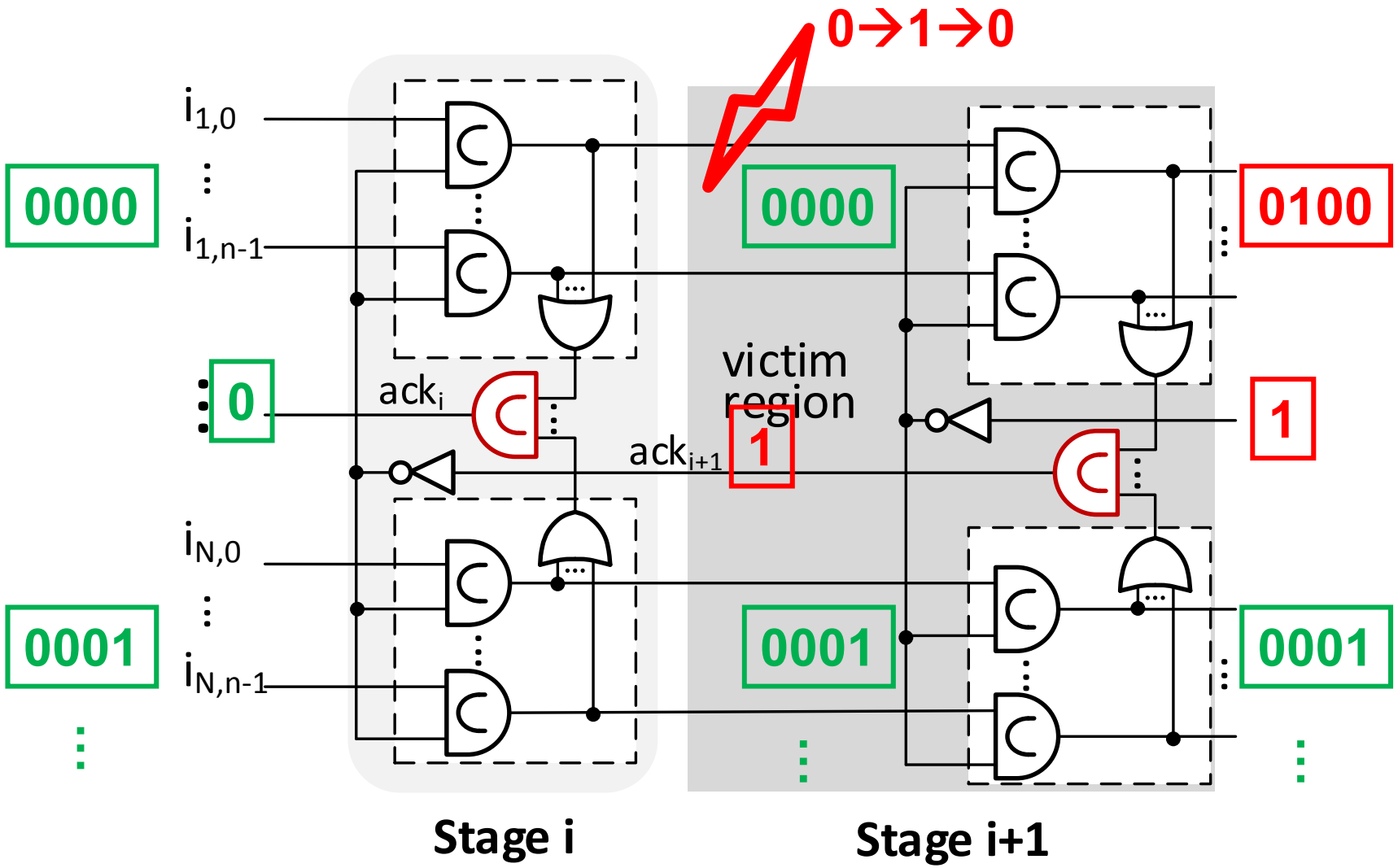
# Deadlock of a multi-word pipeline (5/7)



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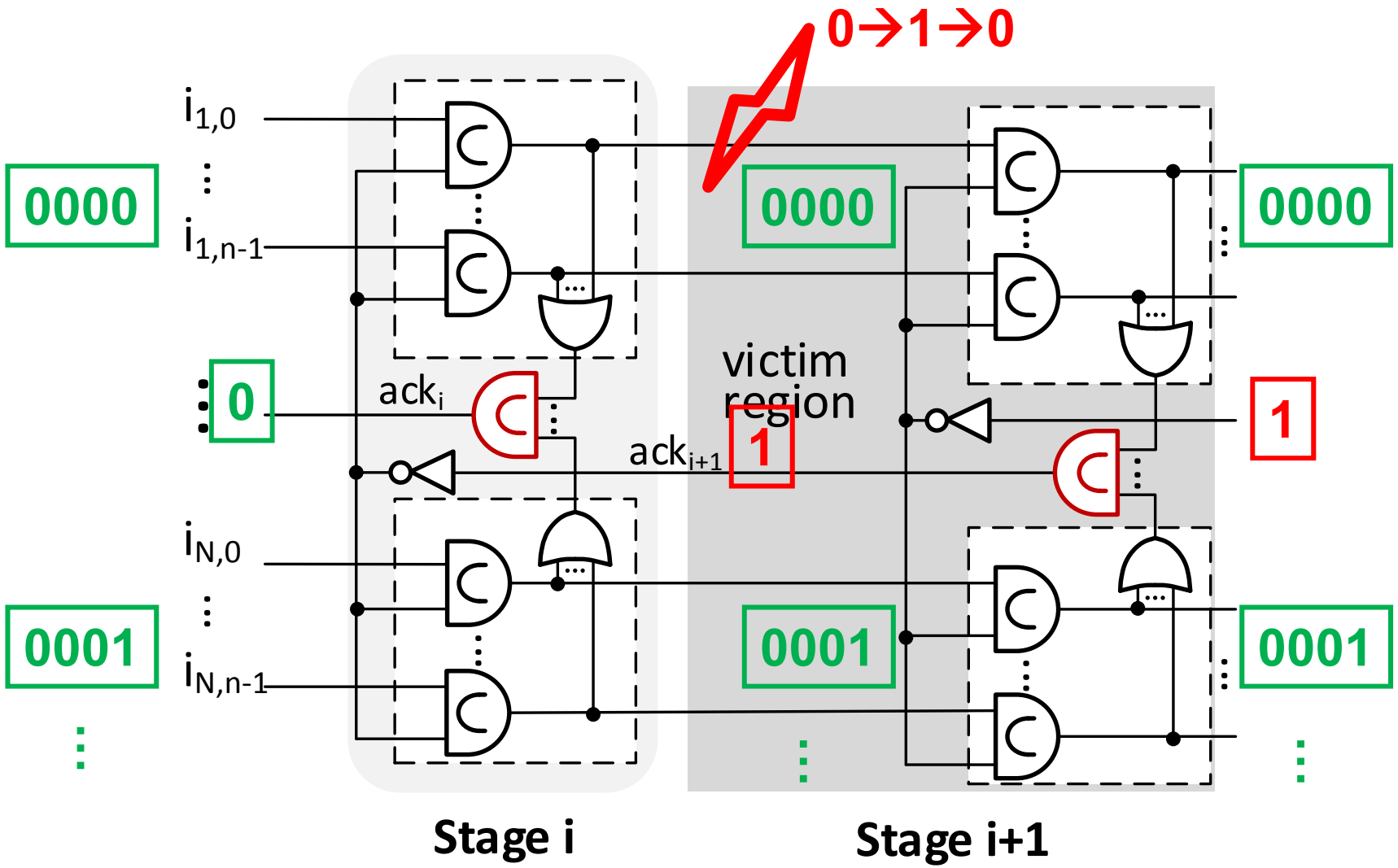
# Deadlock of a multi-word pipeline (6/7)



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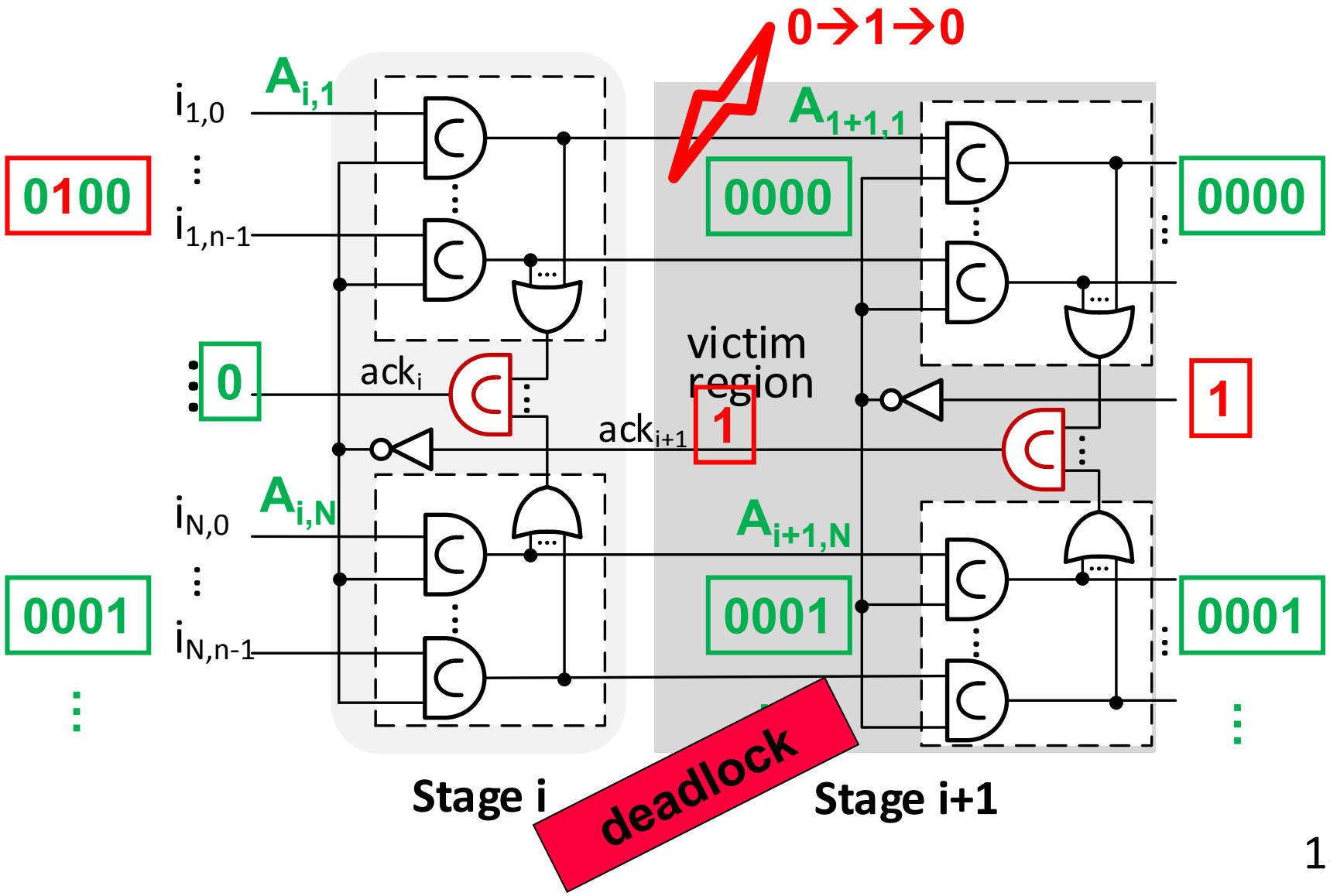
# Deadlock of a multi-word pipeline (7/7)



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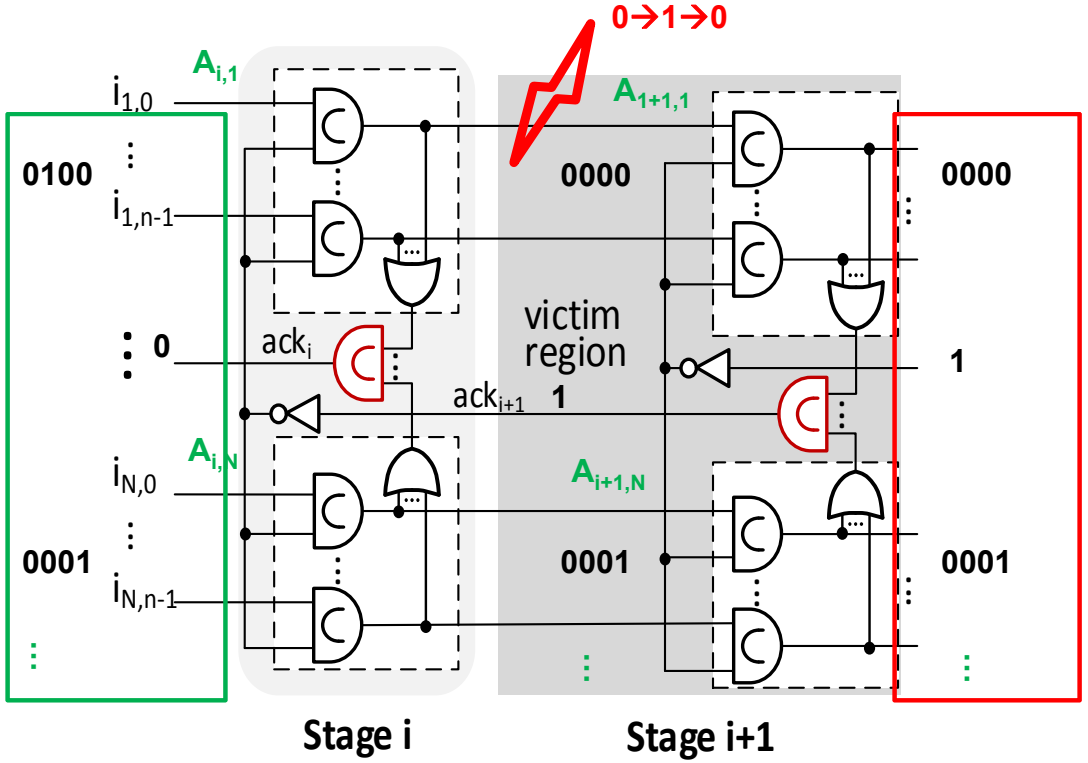
# Deadlock pattern comparison

***Positive transient fault:***

| | ***Pre-fault*** | ***Post-fault*** |
|---|---|---|
| $(\{A_{i,1},\ldots, A_{i,N}\}, ack_i, \{A_{i+1,1},\ldots, A_{i+1,N}\}, ack_{i+1}) =$ | $(\{1,\ldots,1\}, 0$ ***complete*** | $\{0,1,\ldots,1\}, 1)$ ***almost full*** |



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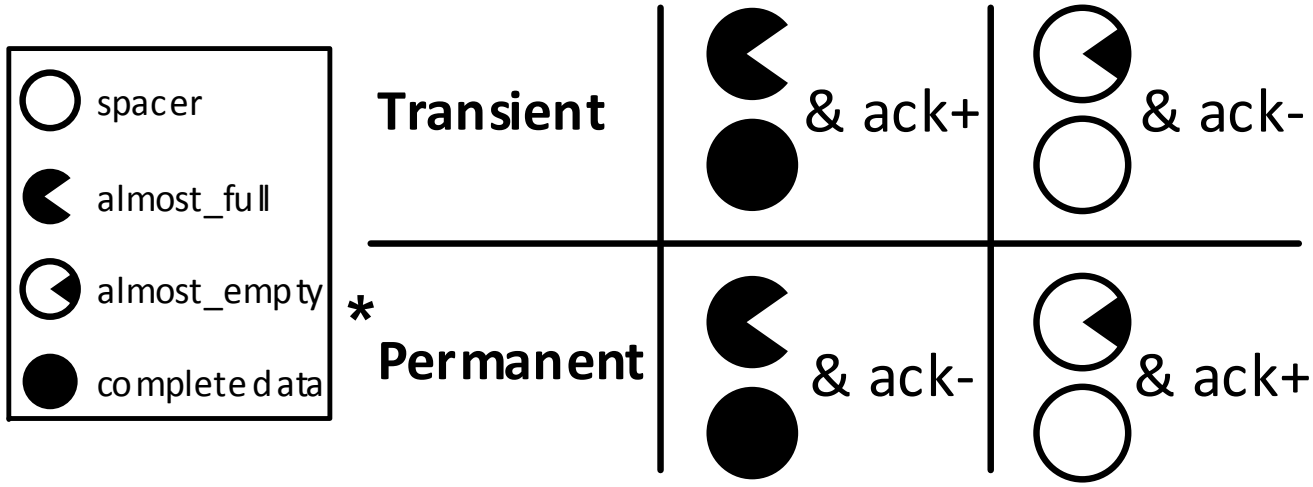
# Deadlock pattern comparison
(transient or permanent)




ft_type ={(almost_full & !ack) | (almost_empty & ack);

((almost_full & ack) | almost_empty & !ack)}

00: default;  01:transient;  10: permanent;  11: invalid



* G. Zhang, etc., “An asynchronous SDM network-on-chip tolerating permanent faults,” ASYNC 2014

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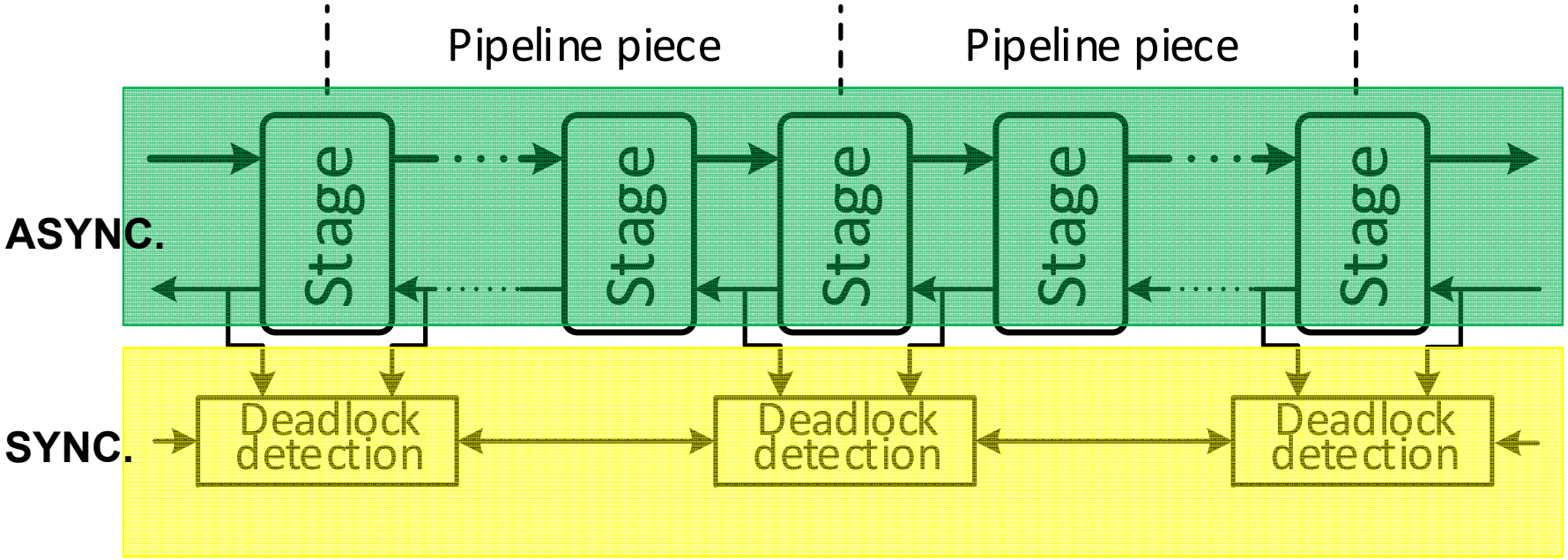
# A general deadlock detection architecture



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# Deadlock detection

- **Usual network deadlock/congestion**
- **Deadlock due to permanent/transient faults**

1. No transitions (a time-out)
2. All pipeline stages downstream of the fault have the same *ack* while the *ack* signals in stages upstream of fault are alternately valued (**deadlock by faults**)
3. ft_type ={(almost_full & !ack) | (almost_empty & ack); ((almost_full & ack) | almost_empty & !ack)}

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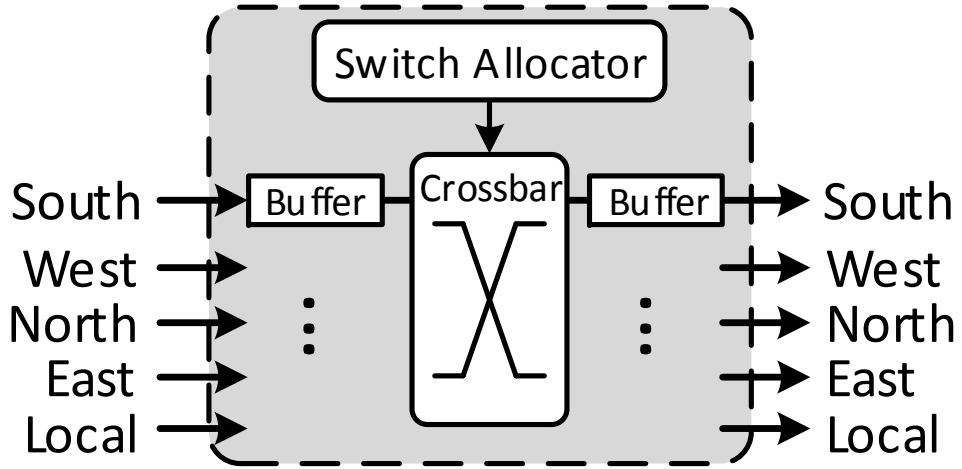
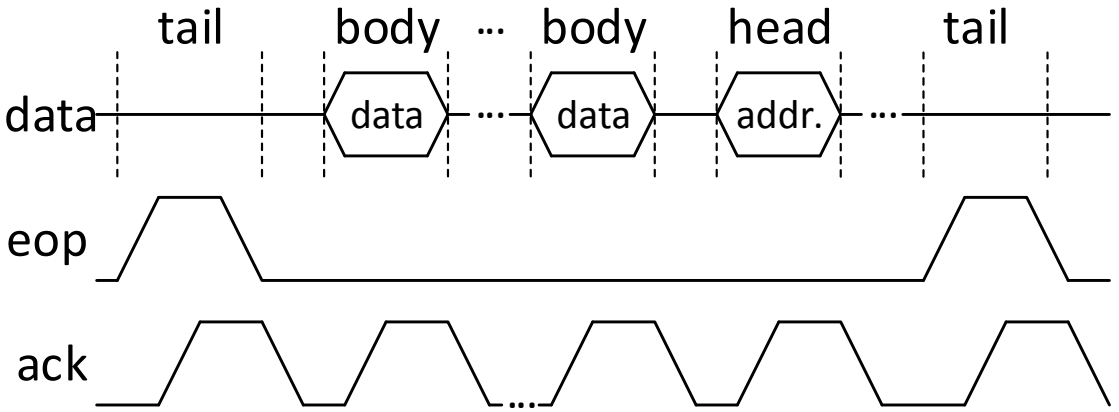
# Network configuration

- 2D mesh QDI NoC
- 4-phase 1-of-4
- Wormhole & XY-DOR



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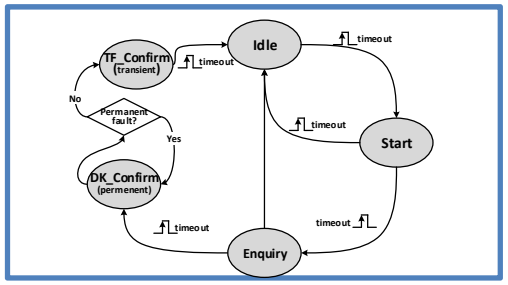
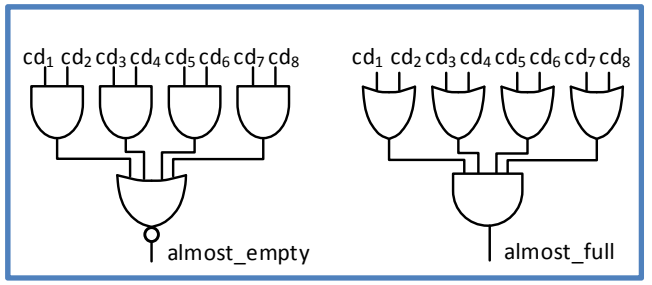
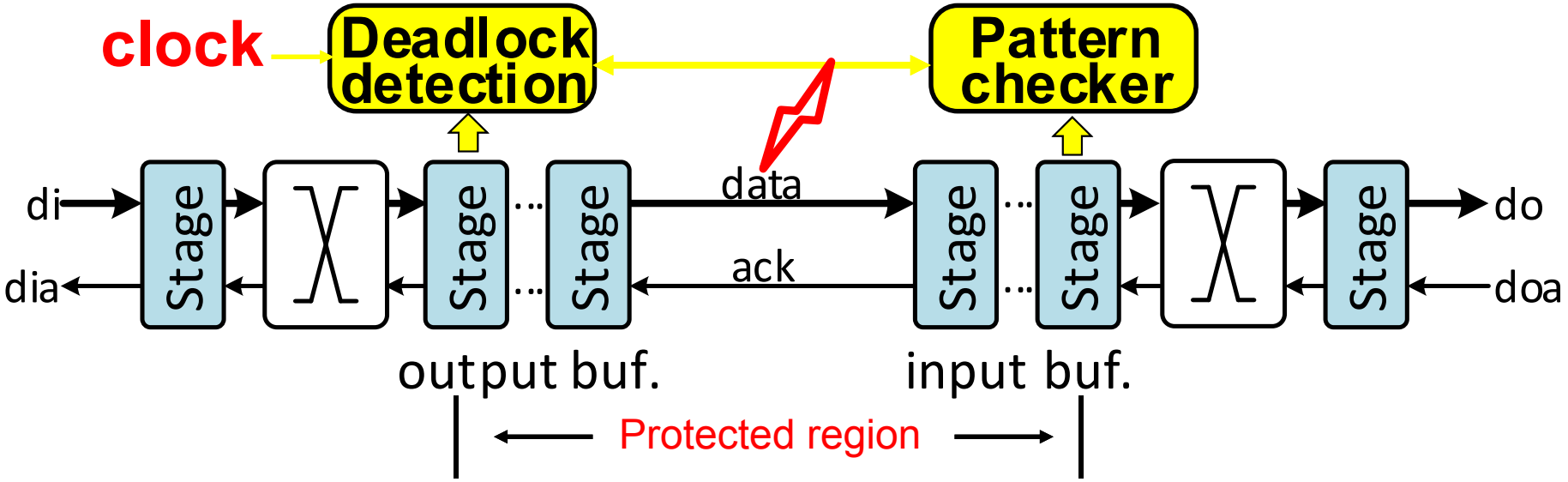
# Deadlock detection



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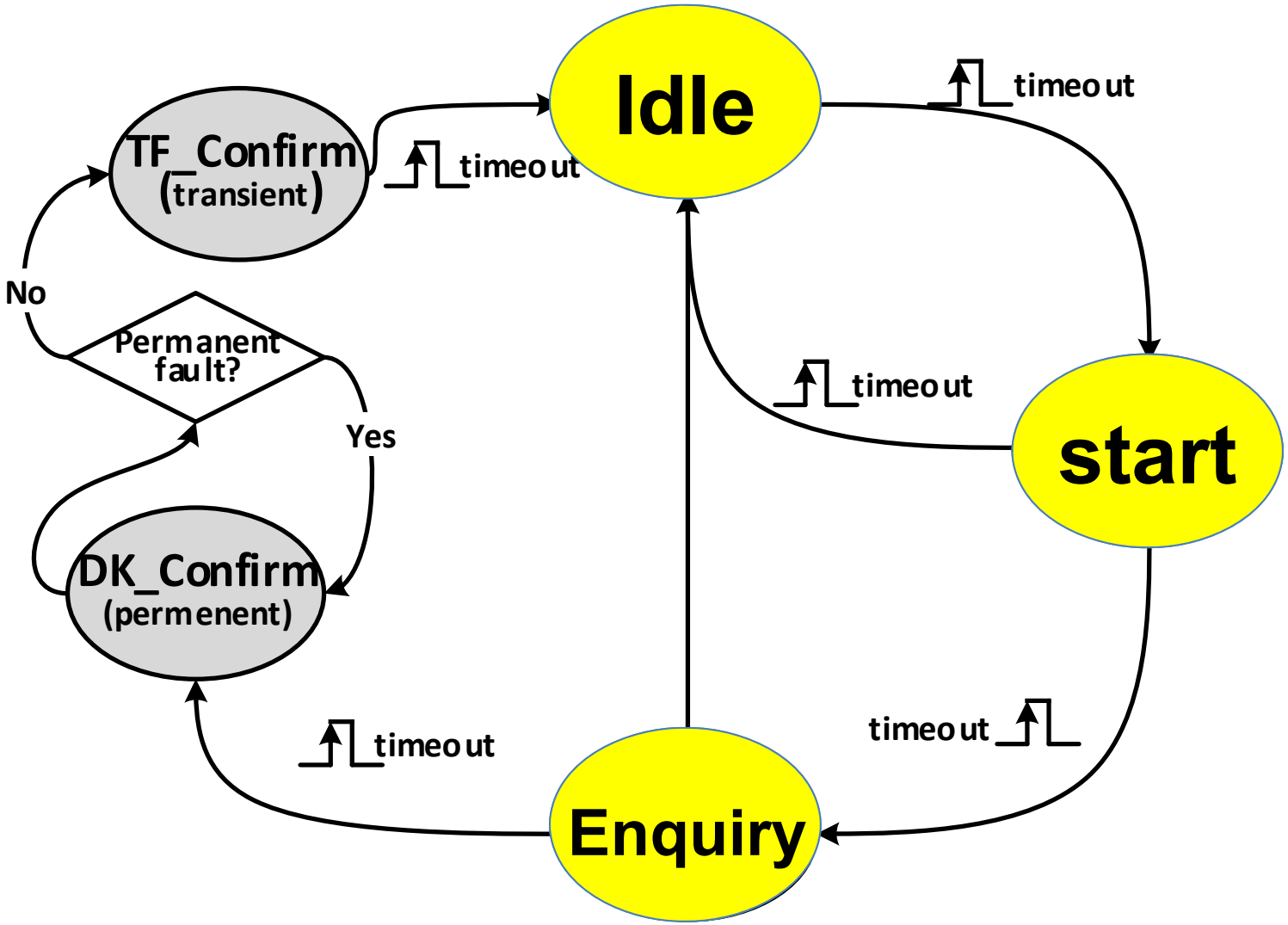
# Deadlock detection



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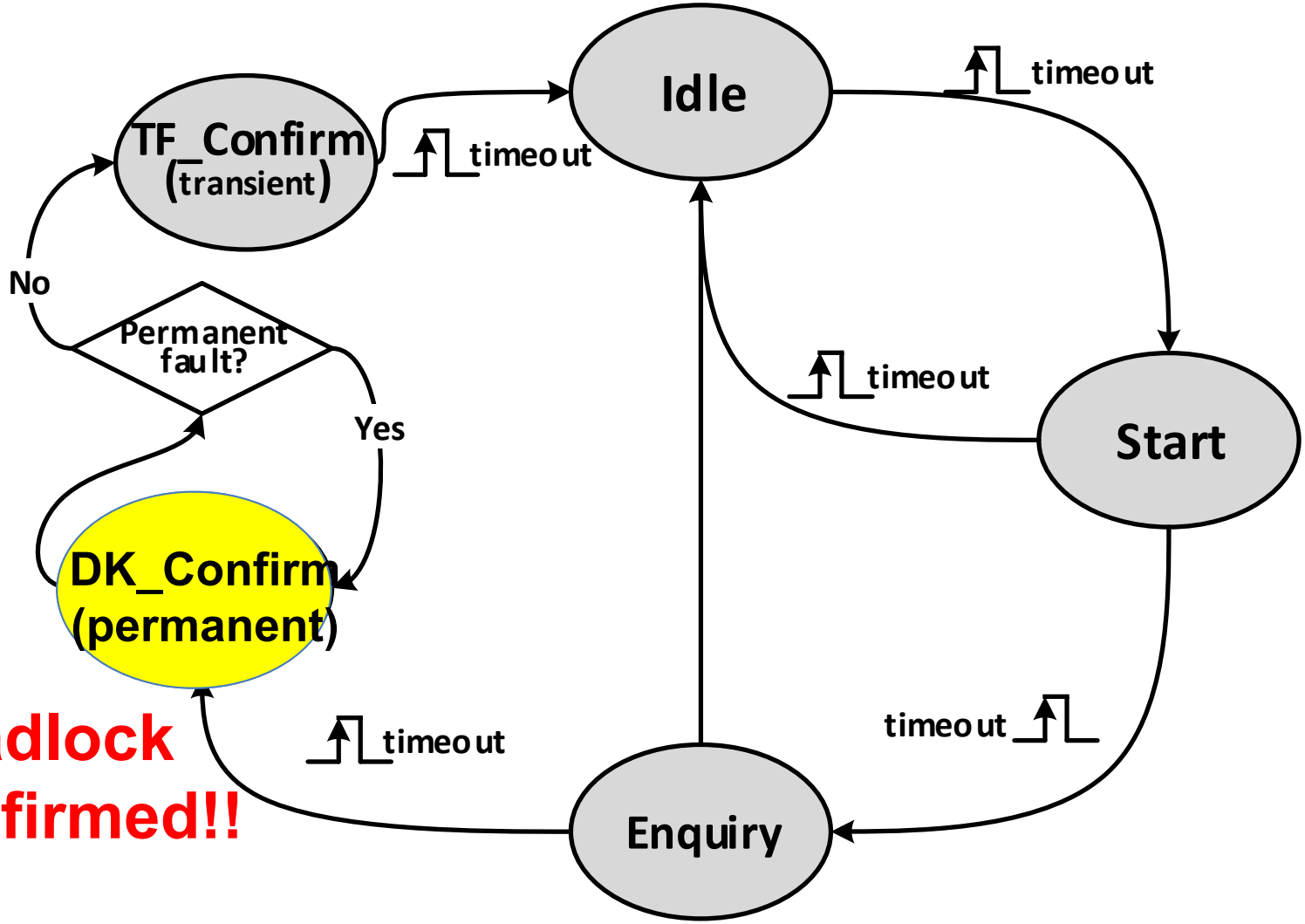
# Deadlock detection




**Deadlock confirmed!!**

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## Deadlock recovery

1. Permanent fault?

**Spatial division Multiplexing (SDM)** to divide each link into physically separated sub-links

- Block the defective sub-link
- Reconfigure the switch allocator
- Drain the flits polluted by the faults from the network

*G. Zhang, etc., “An asynchronous SDM network-on-chip tolerating permanent faults,” ASYNC 2014

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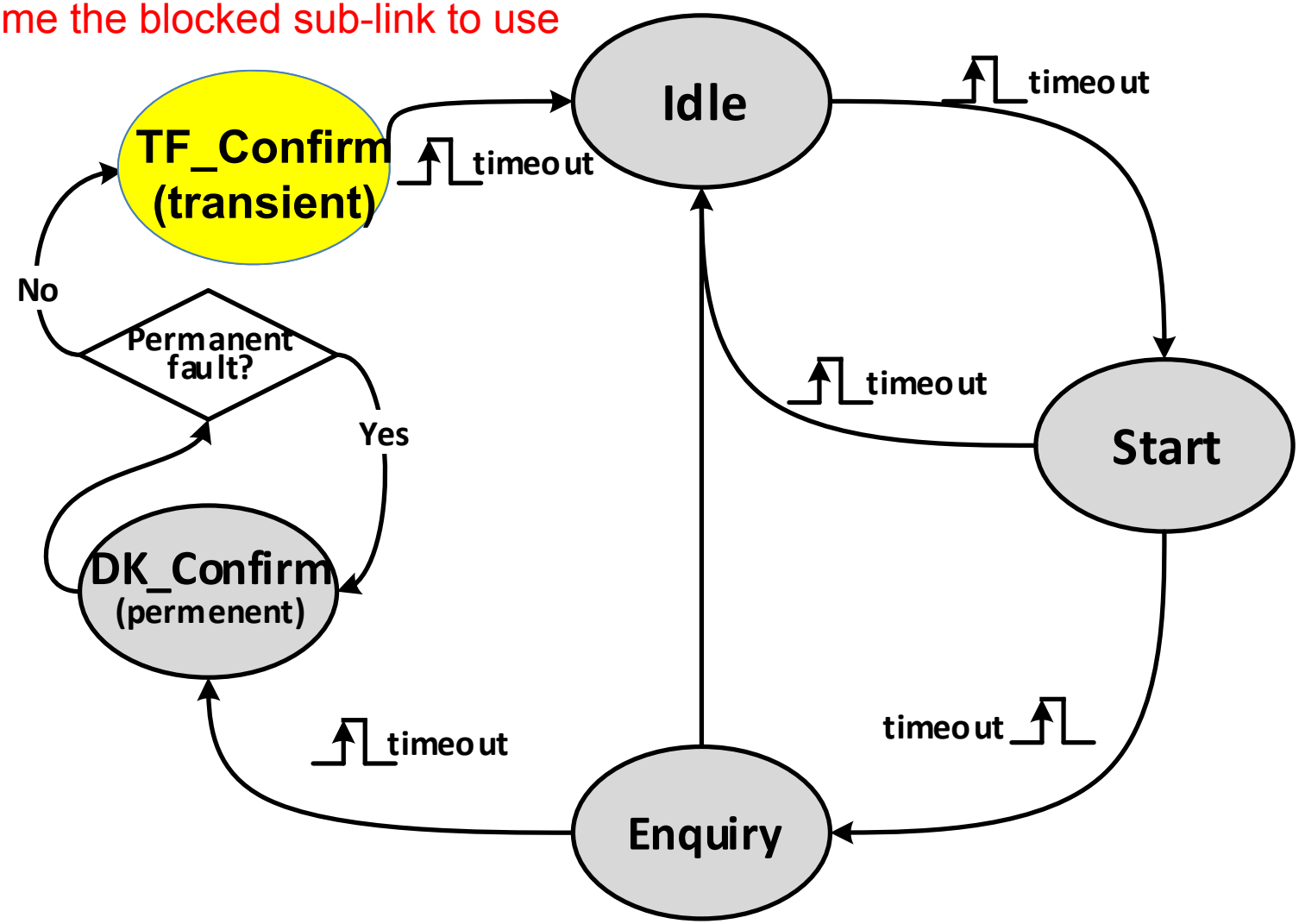
# Deadlock recovery

Resume the blocked sub-link to use



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# Experimental Results

- UMC 130nm standard cell library
- Synchronous IP cores (SystemC) + post-synthesis routers
- 4 × 4 mesh 4-phase 1-of-4 SDM NoC
- packet size: 64 bytes; Local clock: 100MHz;  Time-out: 1.5MHz

| | Original | Protected | Overhead |
|---|---|---|---|
| **Area (um2)** | **63446** | **72394** | **14.1%** |
| **Throughput (Mbyte/s/node)** | **693** | **648** | **-6.5%** |
| **Energy (pJ/Byte)** | **3.7** | **4.3** | **16%** |

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# Conclusion

- If the time difference between two slowest sub-pipelines are longer than the loop latency, a transient fault at the slowest sub-pipeline could cause deadlock.
- The patterns of the deadlock caused by transient faults, congestion and the usual deadlock are different, which can be used to detect the deadlock and tell its kind.
- For deadlock caused by transient faults, a fine-grained recovery mechanism is proposed to recovery the network to avoid expensive system reboot.

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# Thanks for your listening

# Questions?

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**University of Manchester**