Formal Validation of Deadlock prevention in Networks-on-Chips

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Radboud University, Nijmegen

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Outline

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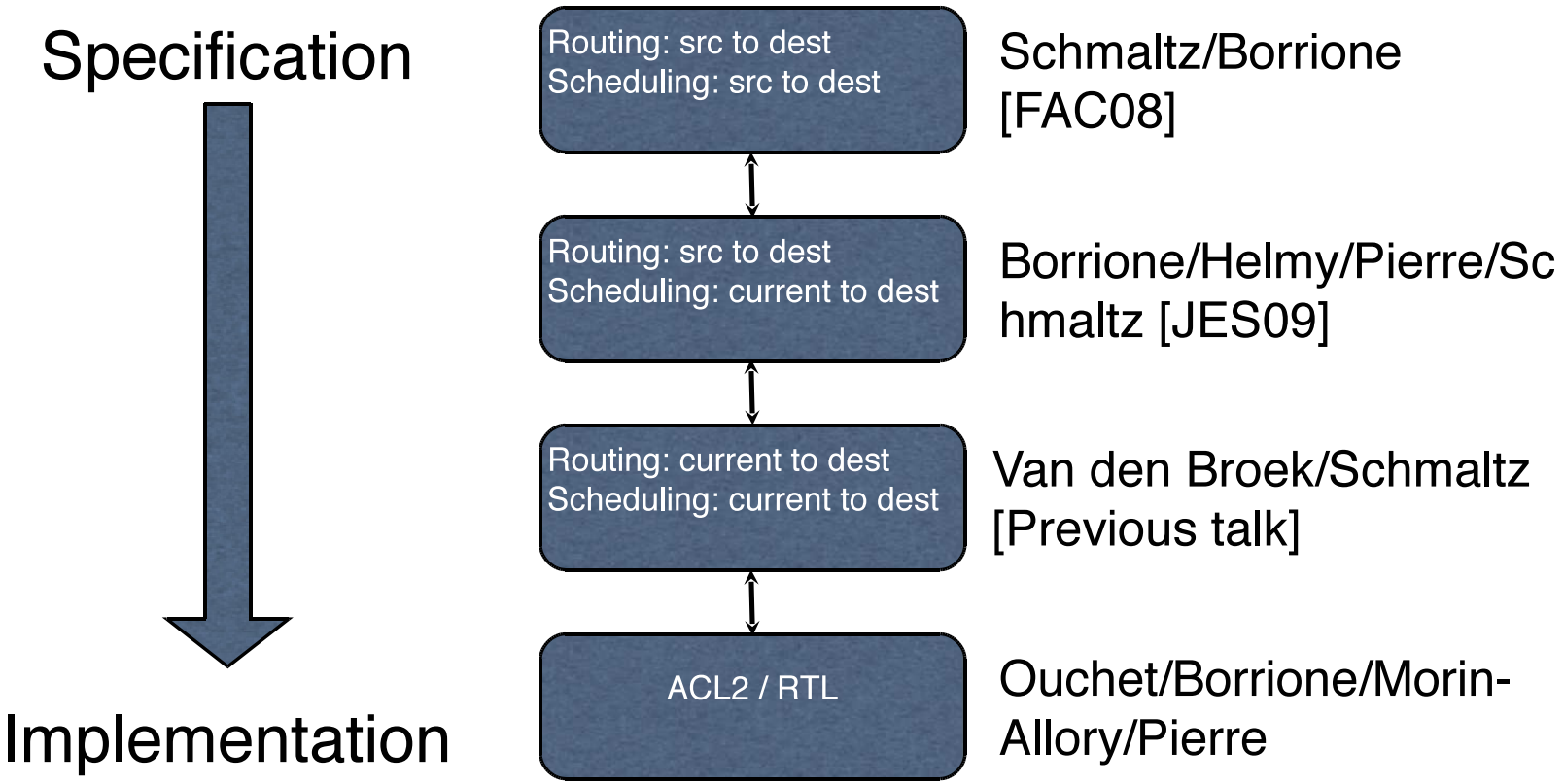
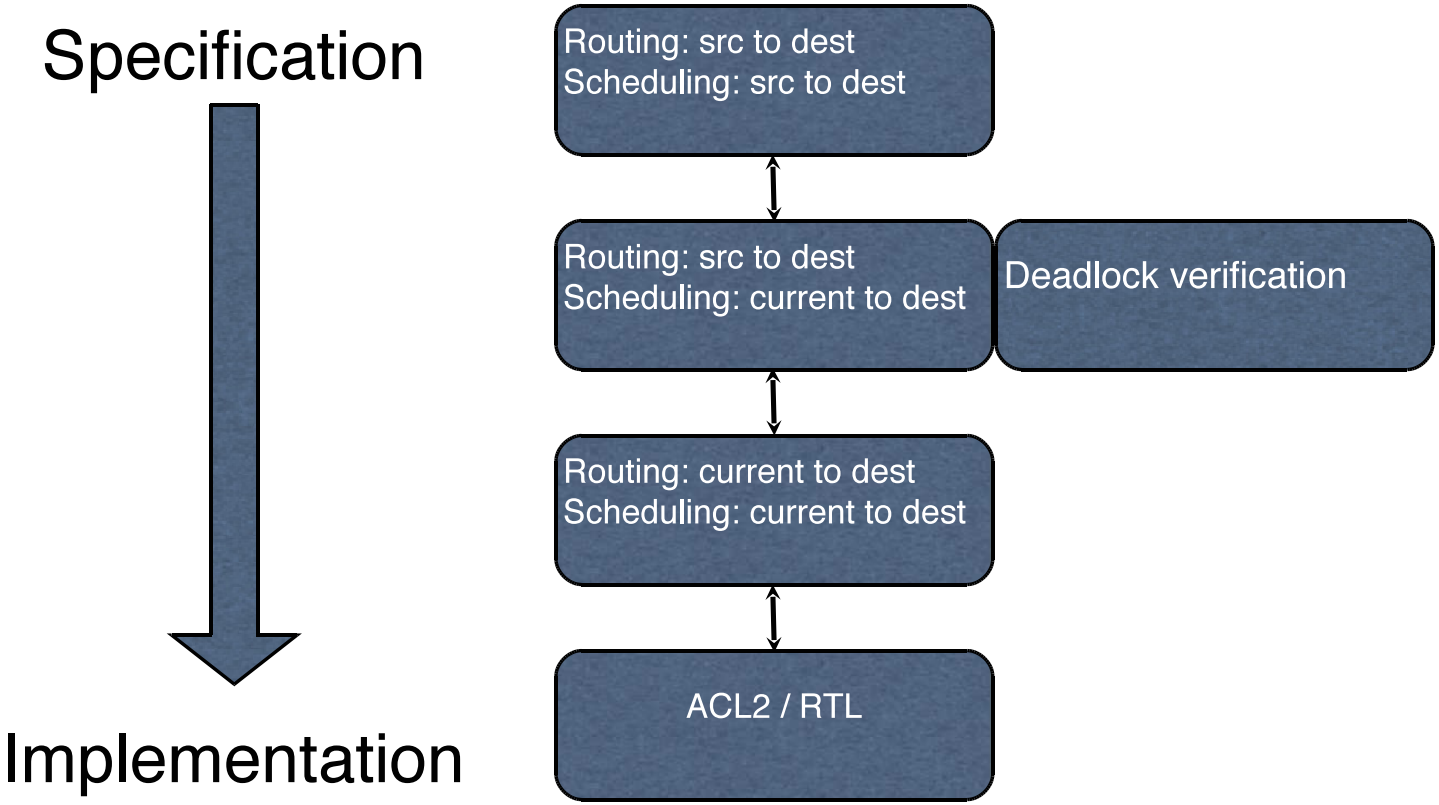
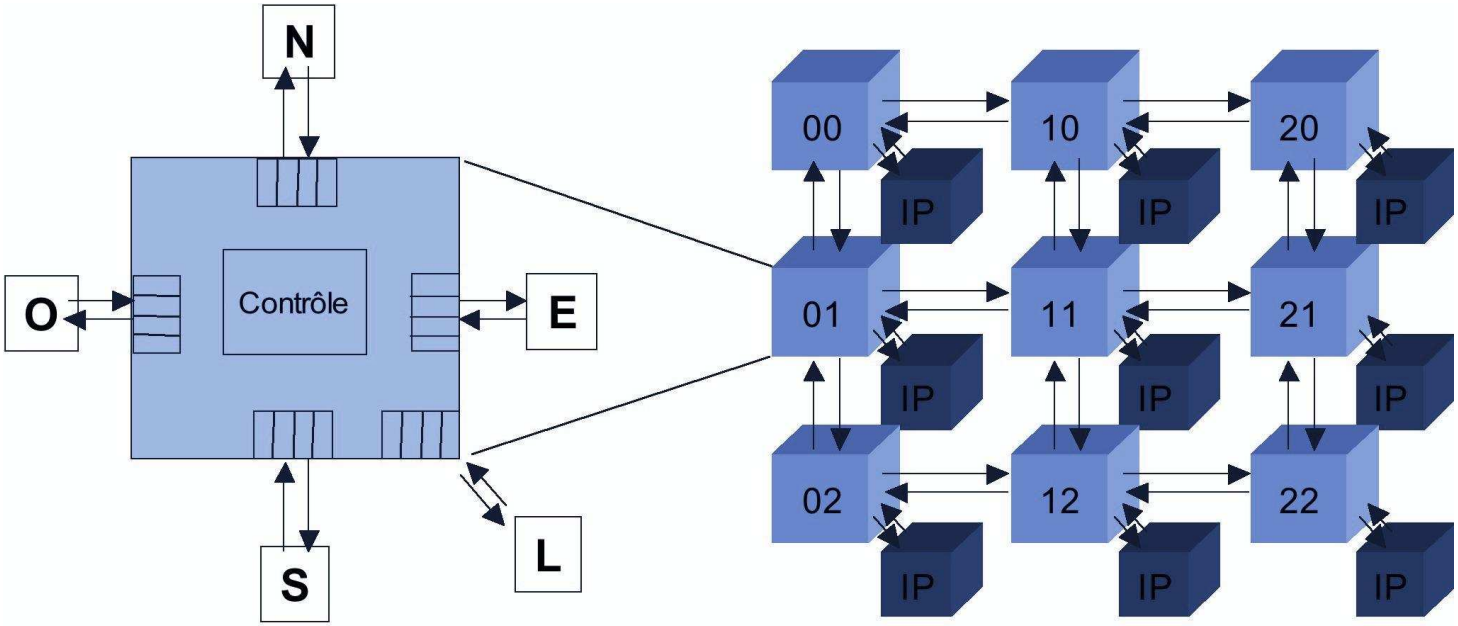
The GeNoC Stack



Contribution



The HERMES Network-on-Chip



Moreas et al. 2004

Constituents

Nodeset	Routing
Injection	Scheduling

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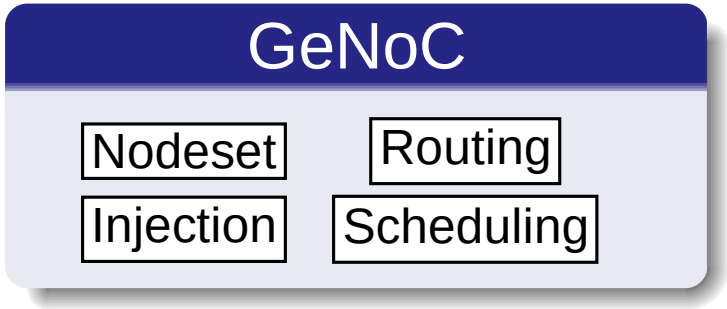
GeNoC for HERMES



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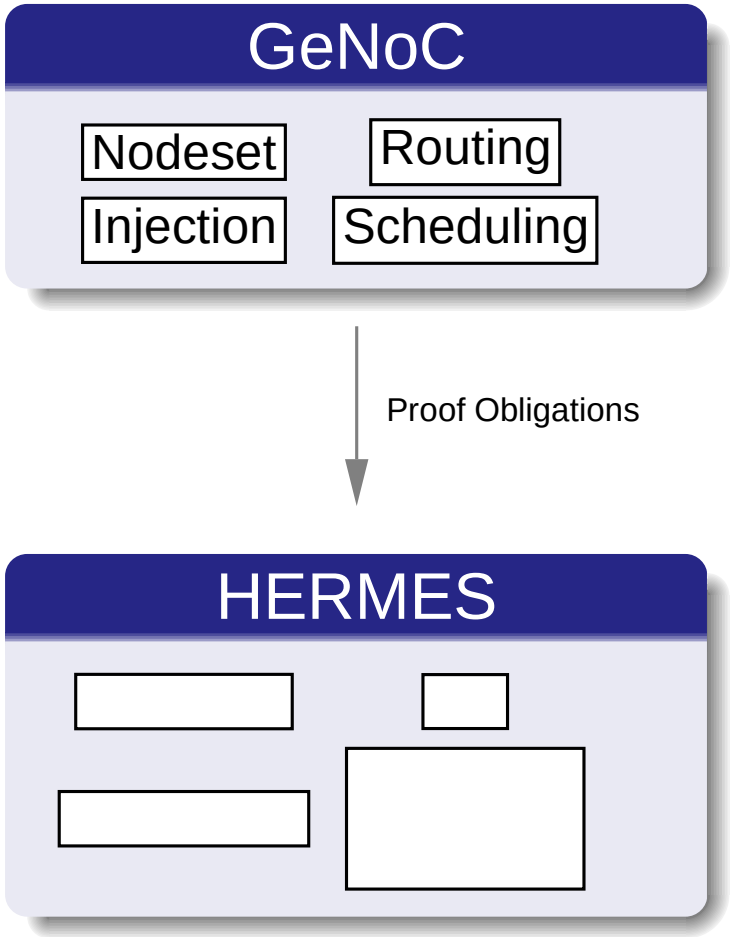

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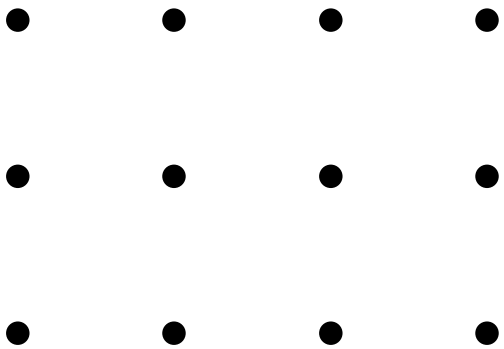

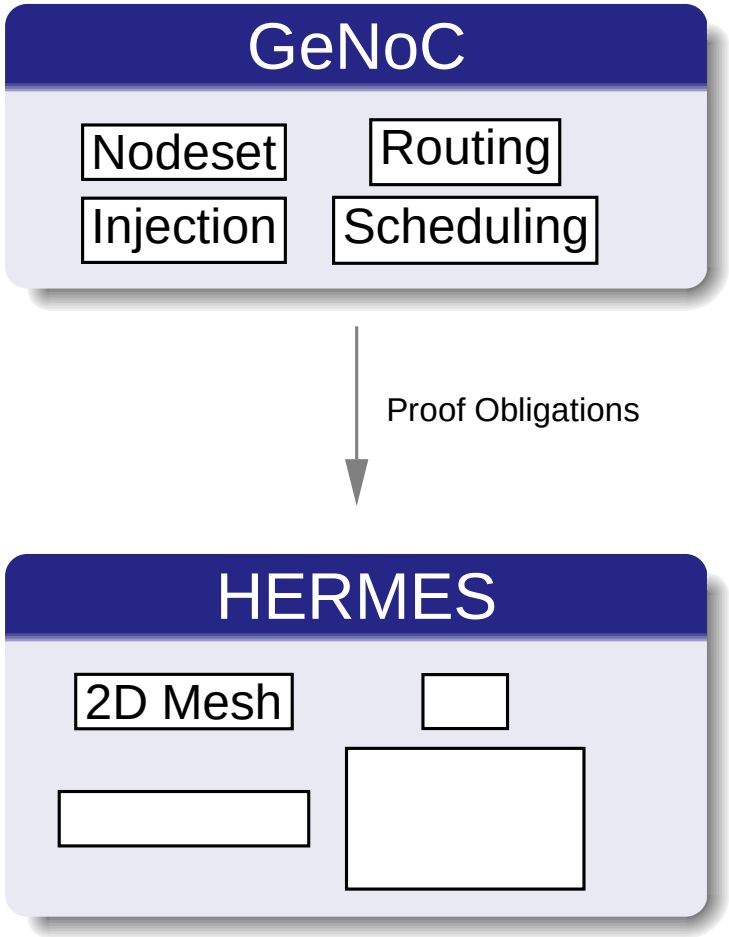

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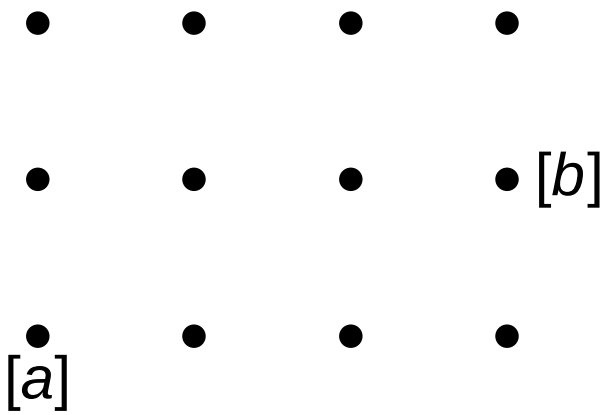

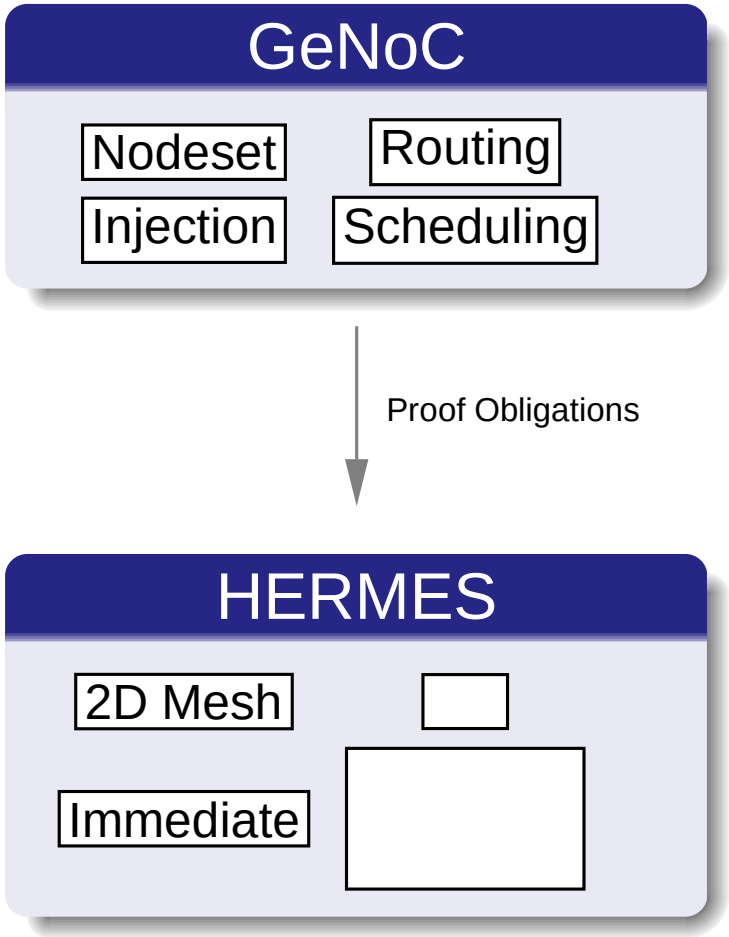

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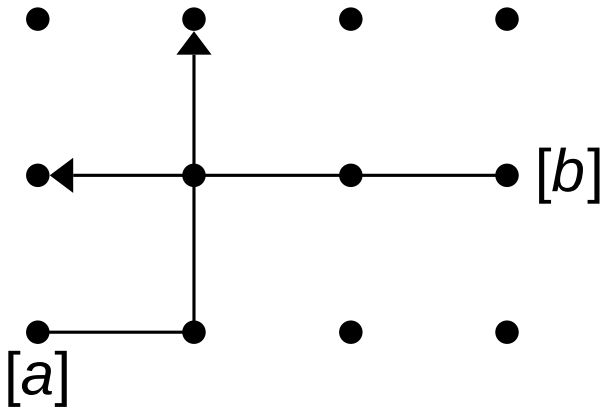

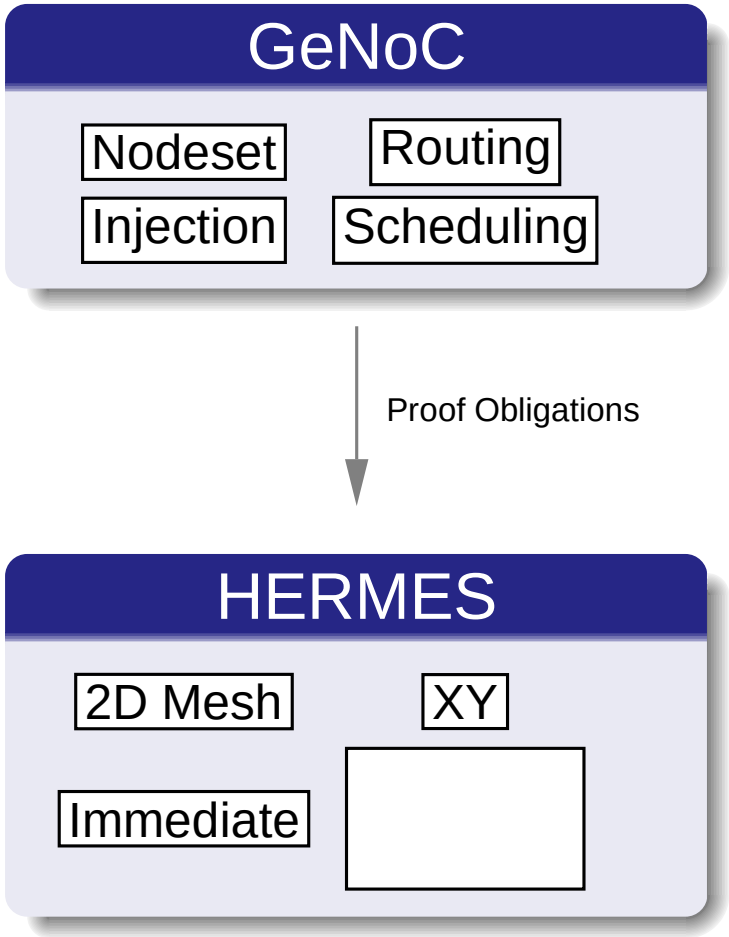

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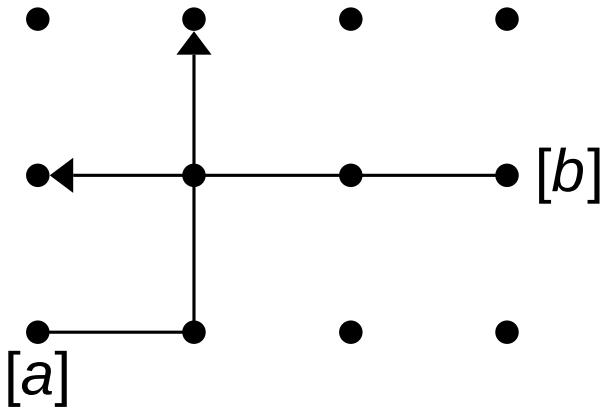

GeNoC

Nodeset | Routing | Injection | Scheduling

Proof Obligations

HERMES

2D Mesh | XY | Immediate | Circuit Switching

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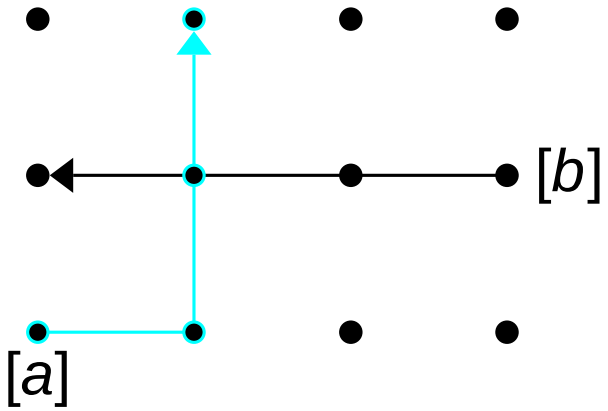
GeNoC for HERMES



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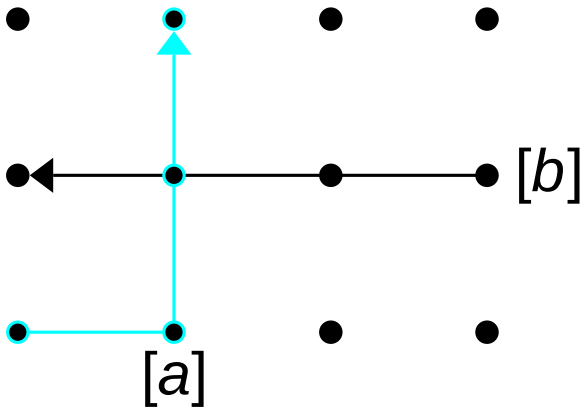

GeNoC

Nodeset | Routing

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Proof Obligations

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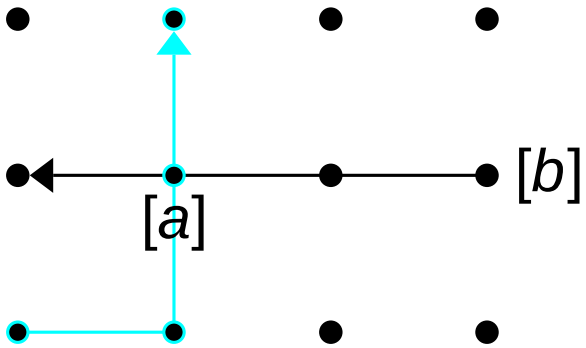

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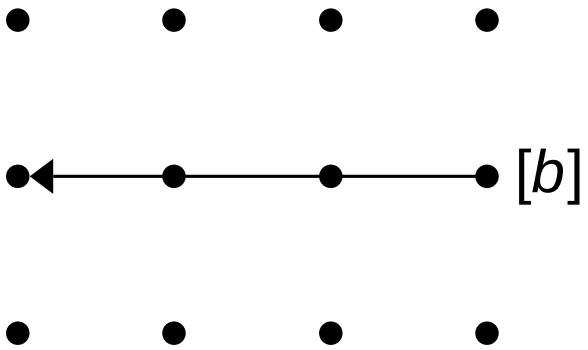

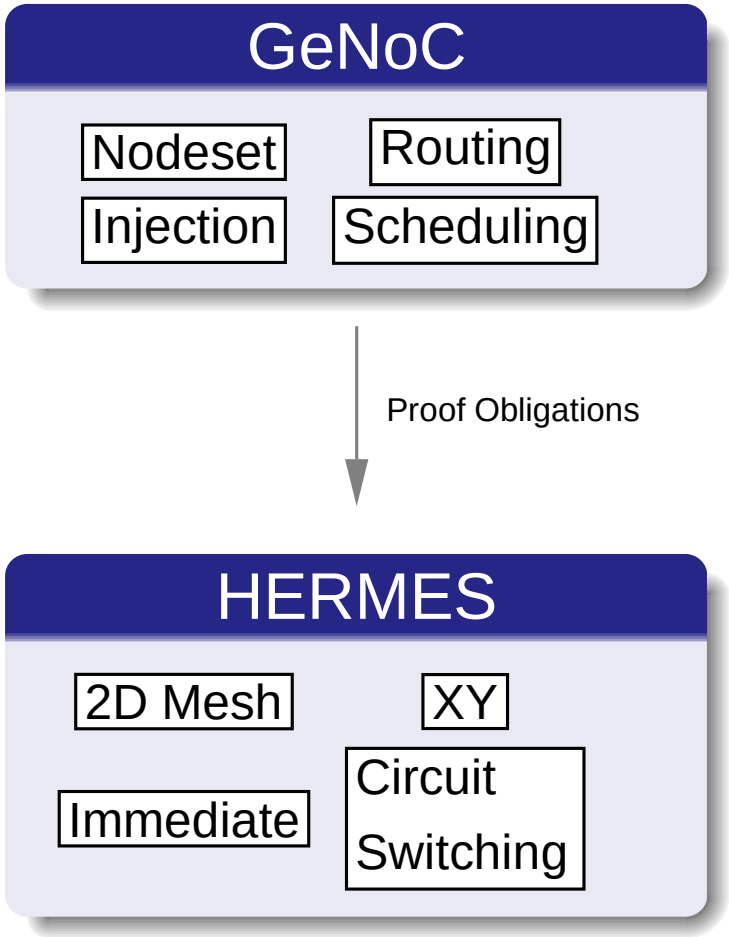

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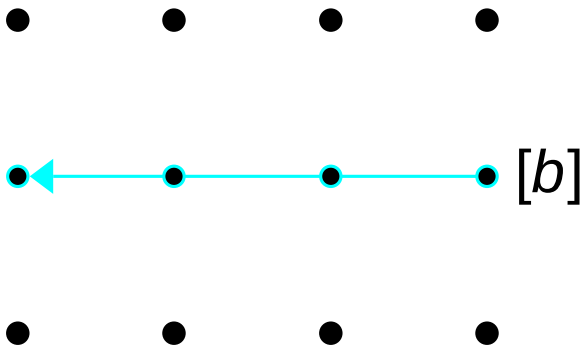

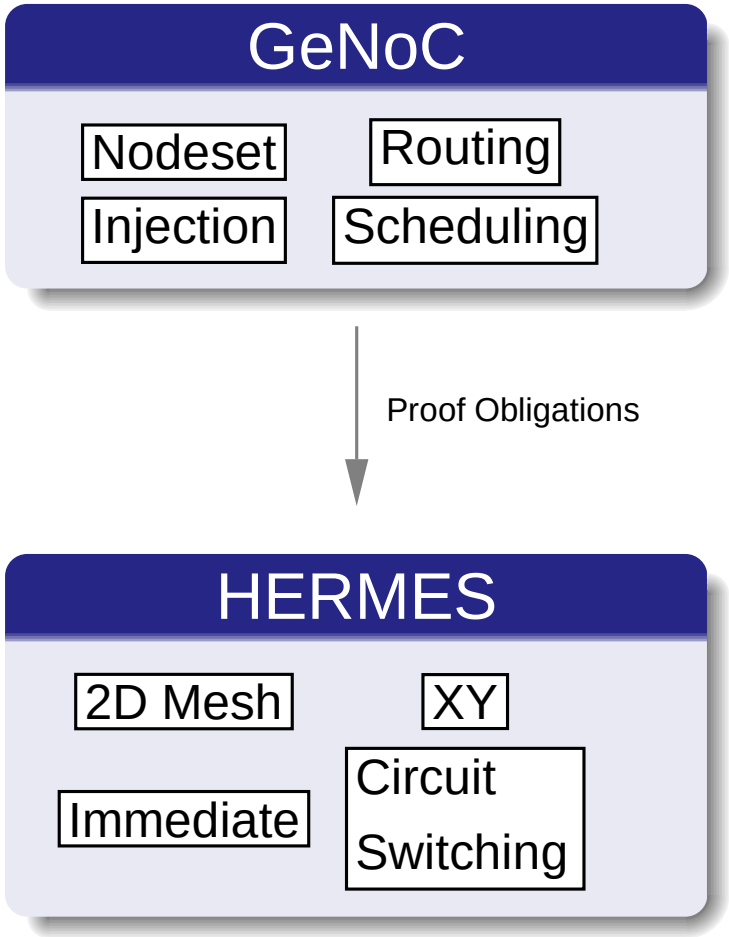

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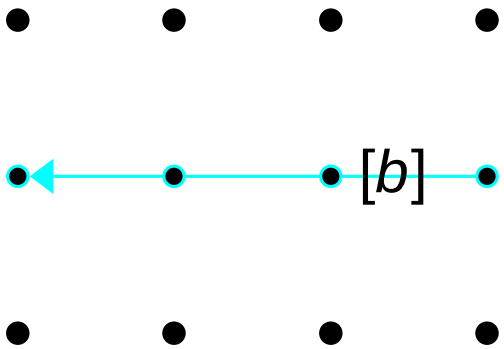

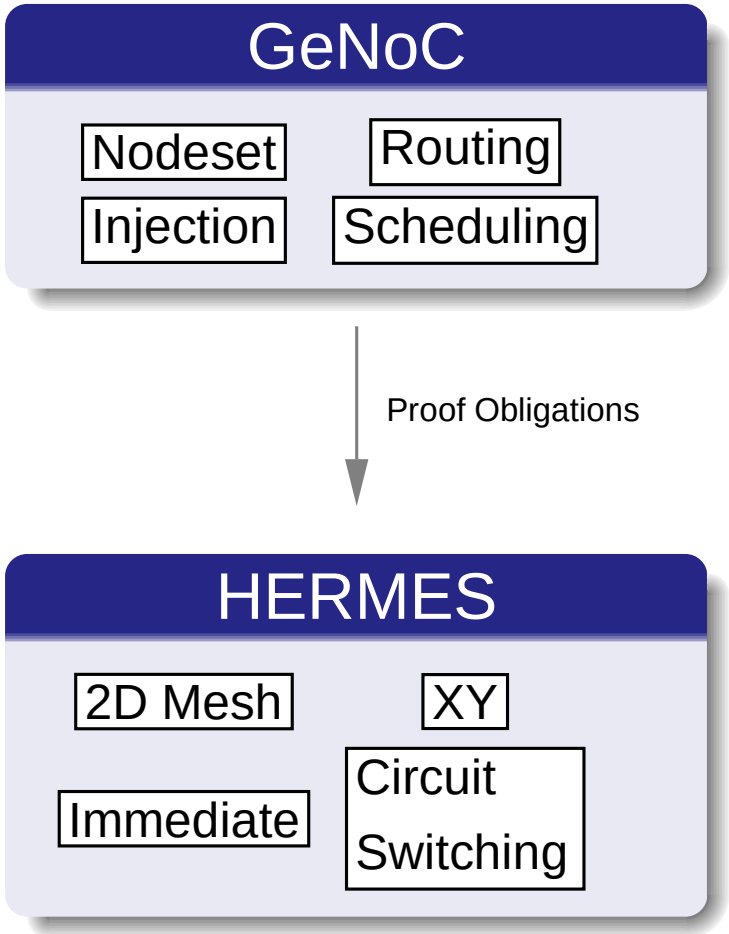

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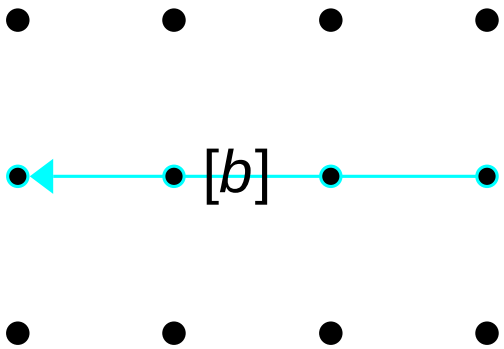

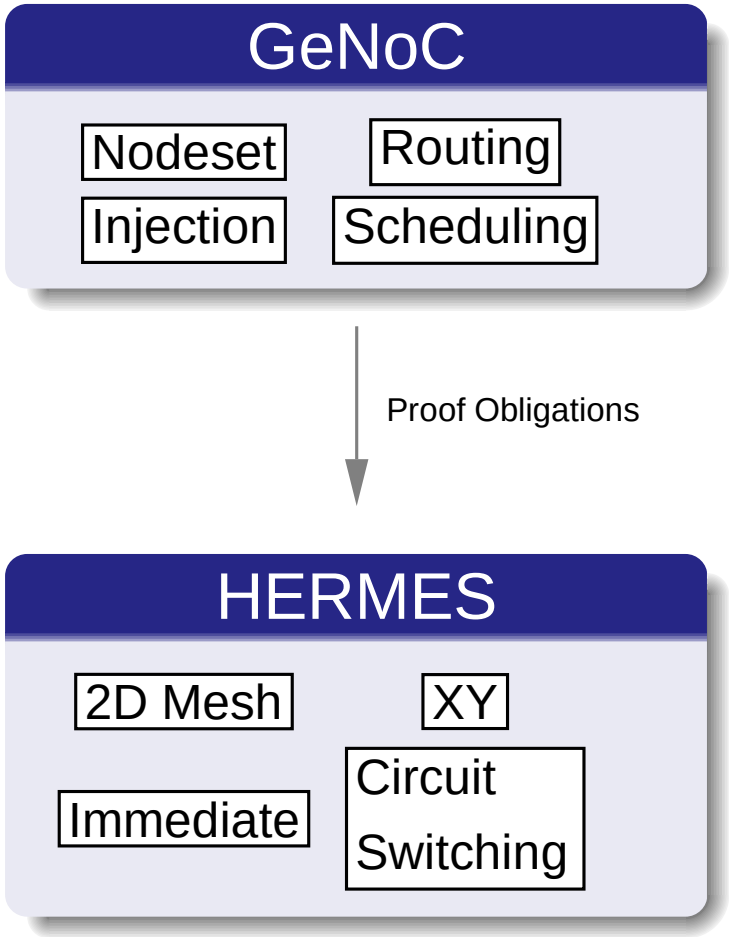

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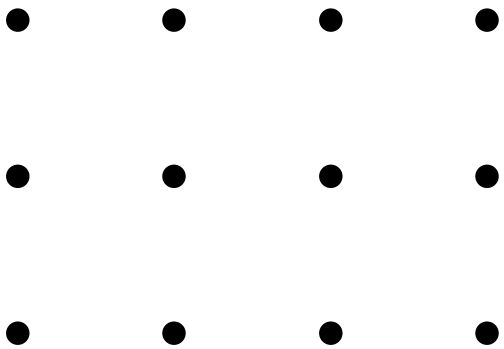

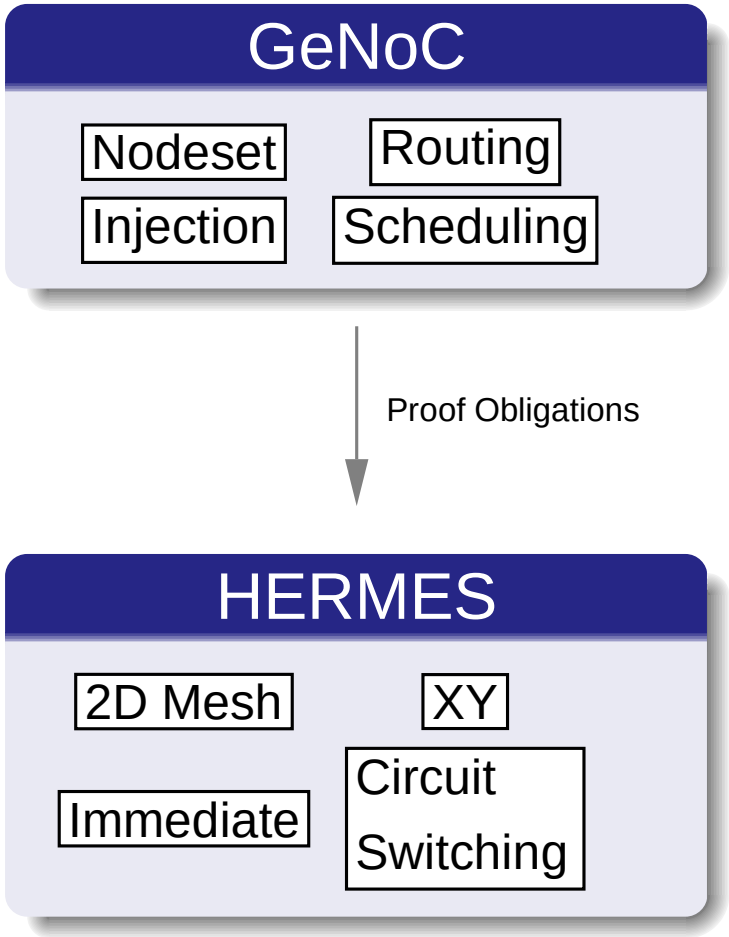

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GeNoC

`trlst` denotes the list of travels
`st` denotes the current state of the network
`arr` stores arrived travels

```
(defun GeNoC (trlst st arr)
  (if (endp trlst)
    (list arr nil)
    (mv-let (delayed enroute)
            (injection trlst st)
            (let ((enroute' (routing enroute)))
              (mv-let (st' arr')
                      (scheduling st enroute')
                      (GeNoC (append delayed enroute')
                             st'
                             (append arr' arr)))))))
```

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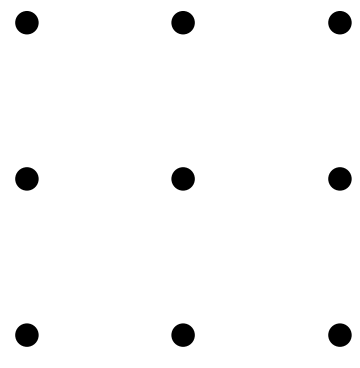
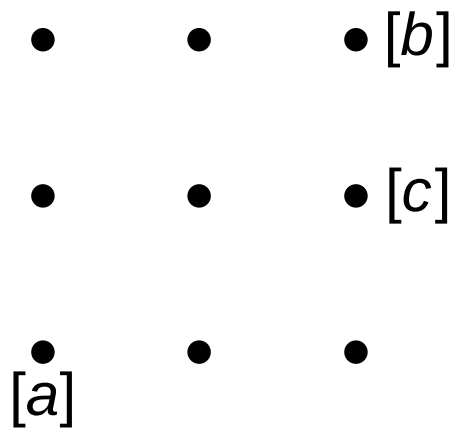


```
trlst = (a, b, c)
arr   = nil
del   =
er    =
er'   =
arr'  =
```

```
(if (endp trlst)
  (list arr nil)
  (mv-let (del er)
    (injection trlst st)
    (let ((er (routing er)))
      (mv-let (st' er' arr')
        (scheduling st er')
        (GeNoC
            (append del er')
            st'
            (append arr' arr)
                        )))))
```

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trlst = (a, b, c)
arr   = nil
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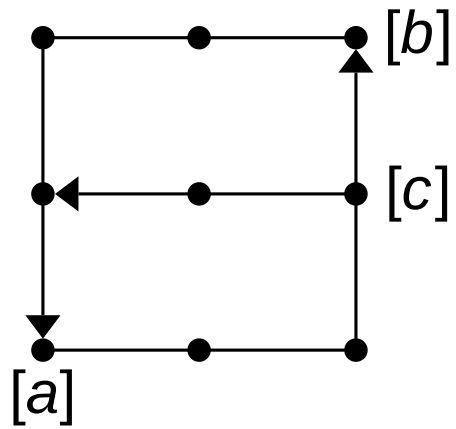


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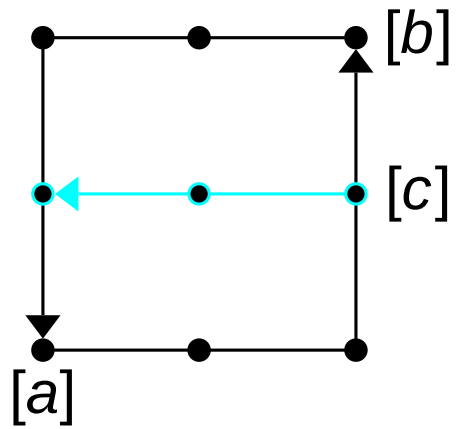


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er    = (a, b, c)
er'   = (a, b, c)
arr'  = nil
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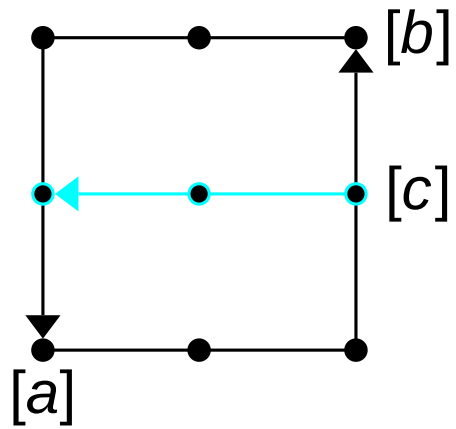


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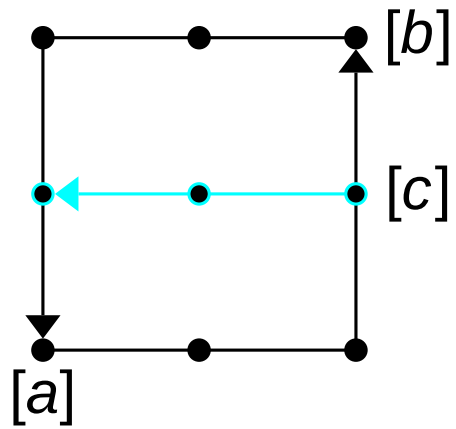


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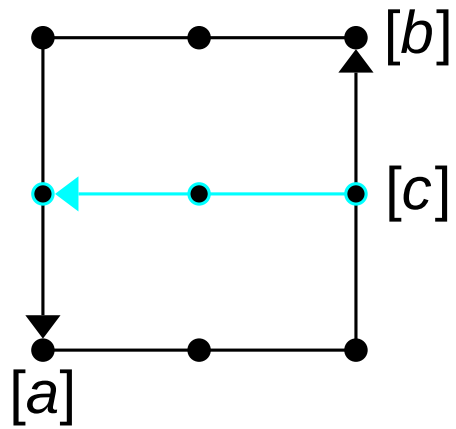


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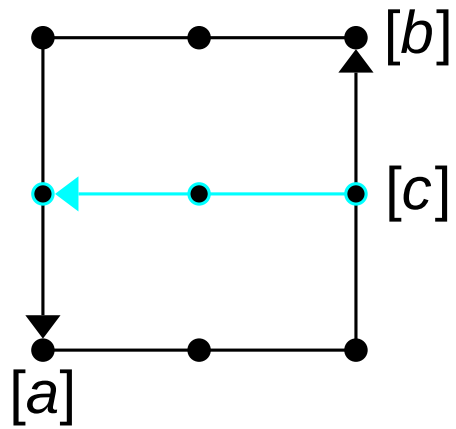


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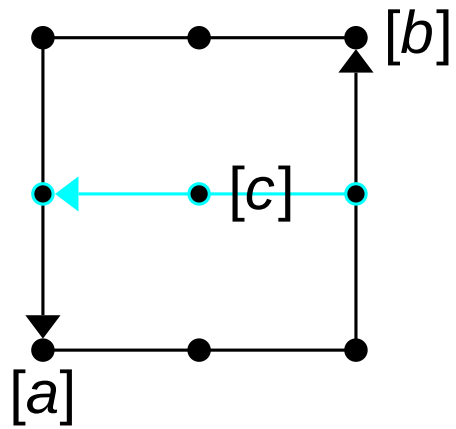


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arr'  = nil
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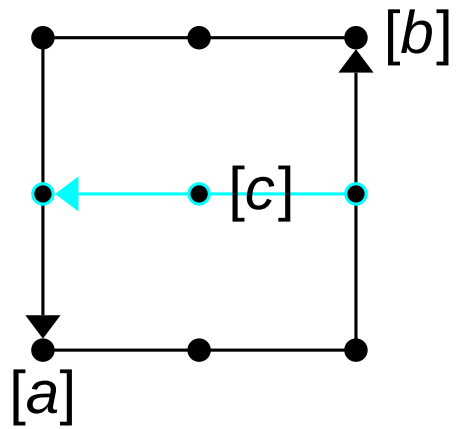


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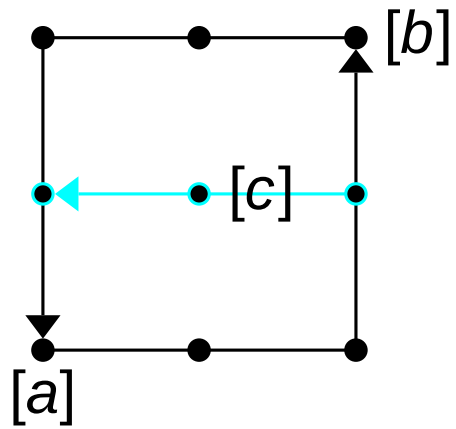


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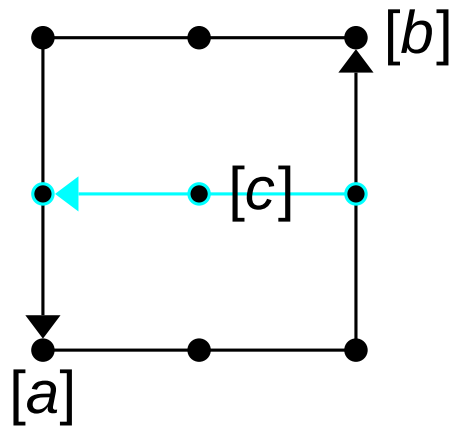


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arr   = nil
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er    = (a, b, c)
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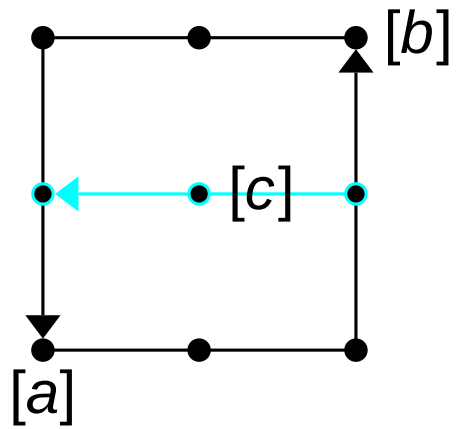


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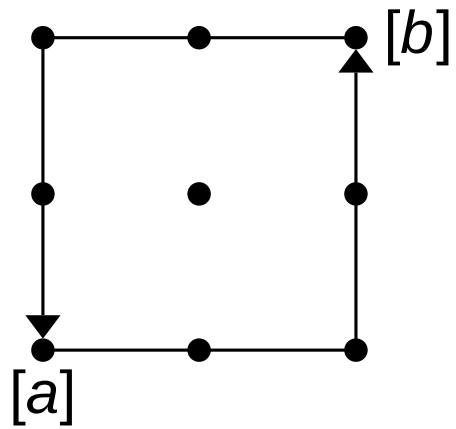


```
trlst = (a, b, c)
arr   = nil
del   = nil
er    = (a, b, c)
er'   = (a, b)
arr'  = (c)
```

```
(if (endp trlst)
  (list arr nil)
  (mv-let (del er)
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    (let ((er (routing er)))
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                        )))))
```

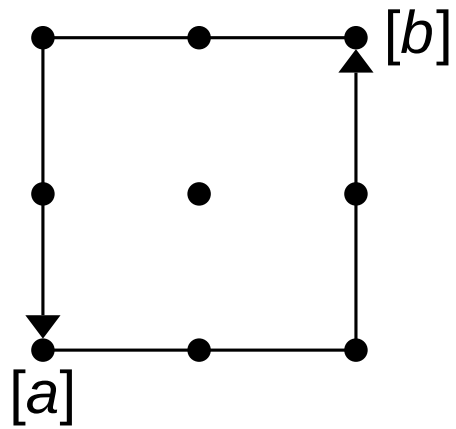


```
trlst = (a, b, c)
arr   = nil
del   = nil
er    = (a, b, c)
er'   = (a, b)
arr'  = (c)
```

```
(if (endp trlst)
  (list arr nil)
  (mv-let (del er)
    (injection trlst st)
    (let ((er (routing er)))
      (mv-let (st' er' arr')
        (scheduling st er')
        (GeNoC
            (append del er')
            st'
            (append arr' arr)
                        )))))
```

Termination of GeNoC

Current situation:

- Measure is sum of attempts of each travel
- Termination of GeNoC $=$ Attempts have been exhausted

Desired situation:

- Termination of GeNoC $=$ 1.) All travels have arrived
  or
  2.) deadlock

Approach

- A *generic measure* is added as parameter to GeNoC:
  1. Generic function `deadlock-statep`
  2. Generic function `measurep`
- New proof obligation:

```
(defthm measure-decreases
  (implies (and (measurep (trlst st meas))
                (not (deadlock-statep trlst st)))
           (O< (acl2-count (mv-nth 2
                                   (scheduling trlst st)))
               (acl2-count meas))))
```

Measure for Circuit Switching

- Measure:

```
(defun ct-measurep (trlst st meas)
  (equal meas
         (sum-of-lst (route-lengths trlst))))
```

- Deadlock-state:

```
(defun ct-deadlock-statep (trlst st)
  (if (endp trlst)
    t
    (and (not (free-nodes (route (car trlst)) st))
         (ct-deadlock-statep (cdr trlst) st))))
```

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```
(if (endp trlst)
  (list arr trlst)
  (mv-let (del er)
          (injection trlst st)
          (let ((er' (routing er)))
            (if (deadlock-statep er' st)
                (list arr trlst)
                (mv-let (st' arr' meas')
                        (scheduling st er')
                        (GeNoC
                             (append del er')
                             st' meas'
                             (append arr' arr)
                                     ))))))
```

Generic proof structure

To prove that a NoC is deadlockfree:

1. Define set of conditions P, such that:

$$P \Longrightarrow \texttt{(not (deadlock-statep))}$$

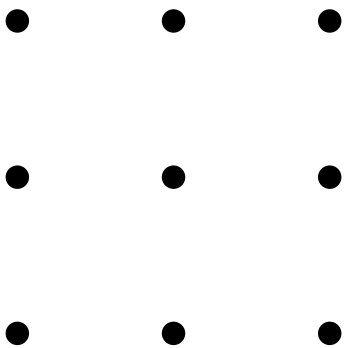
2. Prove that P is inductive for GeNoC

Instantiation

Network:

Nodeset:	$x \times y$ 2D Mesh, b buffers per node
Injection:	Immediate
Routing:	XY Routing
Scheduling:	Circuit Switching with bookings

Deadlock prevention



$b = 3$

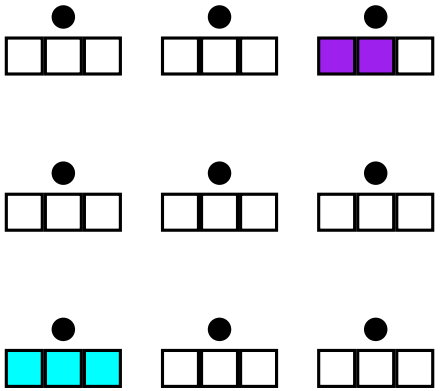
=

Theorem:

Let each node have b buffers.

$$(\texttt{len trlst}) < 2b \implies \text{no deadlock}$$

Deadlock prevention



$b = 3$

$(\texttt{len trlst}) = 5$

Theorem:

Let each node have b buffers.

$$(\texttt{len trlst}) < 2b \implies \text{no deadlock}$$

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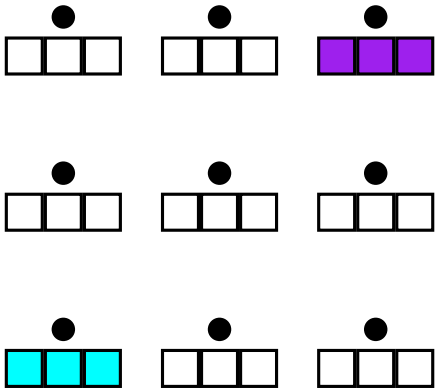
Deadlock prevention



$b = 3$

$(\texttt{len trlst}) = 6$

Theorem:

Let each node have b buffers.

$$(\texttt{len trlst}) < 2b \implies \text{no deadlock}$$

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Proof structure

Generic:

1. Define set of conditions P, such that:

$$P \implies \texttt{(not (deadlock-statep))}$$

2. Prove that P is inductive for GeNoC

Theorem:

$$(\texttt{len trlst}) < 2b \implies \text{no deadlock}$$

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Proof structure

Instantiated:

1. Prove:

$$(\texttt{len trlst}) < 2b \implies$$
at least one travel can advance

2. Prove:

$$(\texttt{len trlst}) < 2b \implies$$
$$(\texttt{len}\,(\texttt{scheduling trlst st}).\texttt{trlst})) < 2b$$

Theorem:

$$(\texttt{len trlst}) < 2b \implies \text{no deadlock}$$

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Theorem

$(\texttt{len}\ \texttt{trlst}) < 2b \implies$ *at least one travel can advance*

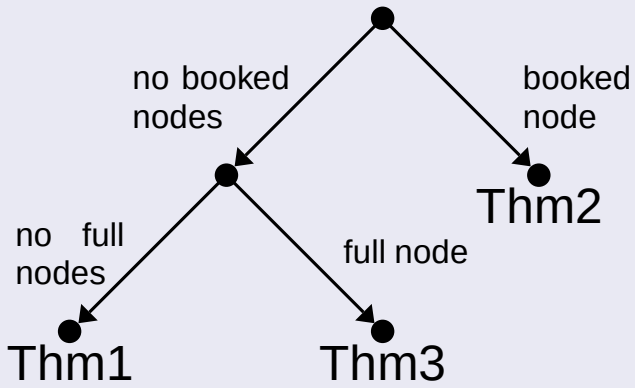
Proof

- A travel can advance if
  1. all nodes of the route are booked, or
  2. all nodes of the route can be booked.
- A node can be booked if
  1. it isn't booked, and
  2. it isn't full.

Theorem

$(\texttt{len}\ \texttt{trlst}) < 2b \implies$ *at least one travel can advance*

Proof



Thm3

No booked nodes and a full node implies any travel currently in the full node can advance.

Proof

Let n be the full node and v be a travel in n:

Thm3.1 The bound on the number of travels implies that for all $n' \neq n$, n' is not full.

Thm3.2 No cycles in routing implies $n \notin \texttt{route}(v)$

Conclusions

- Proven deadlock-prevention theorem by bounding the number of messages.
- Proof consists of 3157 lines: 39 functions and 321 theorems.
- Theorem is proven for any routing, any topology, any nodeset (e.g. ports), and for both circuit and packet switching.
- Defined proof pattern for deadlock-related proofs.

Future work

- Define better bound/set of restrictions.
- Define a more accurate measure than route lengths.
- Prove theorem for wormhole switching.
- Varying injection methods.

Questions?