Timestamp Snooping:
An Approach for Extending SMPs

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http://www.cs.wisc.edu/multifacet/

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Overview

- Problem: multiprocessors for commercial workloads
- Snooping (SMPs)
  + Finds data directly - no indirection
  - Constrains interconnect
- Goal: Free snooping from interconnect constraints
- Timestamps provide logical global order
- Evaluation vs directory protocol (CC-NUMA)
  - Commercial workloads on 16 processors
  - 6-23% faster
  - Directories use17-37% less bandwidth

EXTENDING SMPS TO GENERAL INTERCONNECTS

Outline

- Overview
- Commercial Workloads
- Traditional Coherence
- Timestamp Snooping
    - Interconnect
    - Protocol
- Evaluation
- Conclusion

Commercial Workloads

- Dominant use of multiprocessors

- Moderate processor count

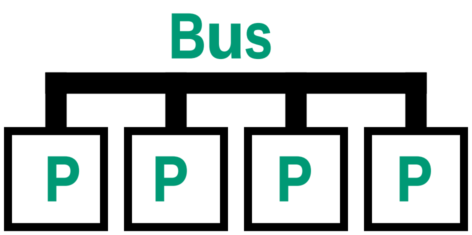
  2-8, then 16-64, but not 1024

- Many cache-to-cache transfers (3-hop or dirty misses)
  - 55-62% for OLTP [Barroso et al. ISCA '98]
  - 40-60% for our commercial workloads

DESIGN MULTIPROCESSORS FOR COMMERCIAL WORKLOADS

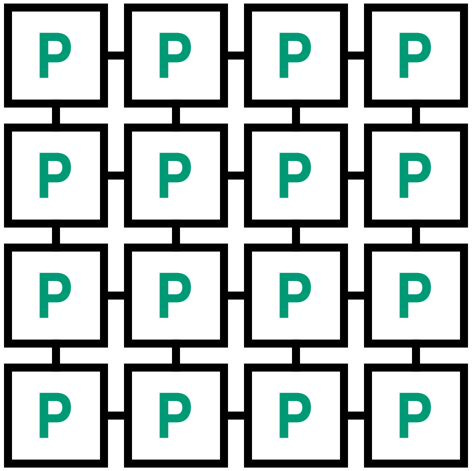
Traditional Snooping (SMPs)

- Operation
  - Requests sent on physical bus
  - Processors & memory *snoop* requests
  - Snoop responses
  - Owner responds
- Advantages
  + Fast cache-to-cache transfers
- Disadvantages
  - Bus bottleneck
  - Signaling limitations
- Agarwal et al. (1988) predicted the demise of SMPs



Directory Protocols (CC-NUMA)

- Add a level of indirection (for some requests)
  - Send requests to *a directory*
  - Directory redirects request

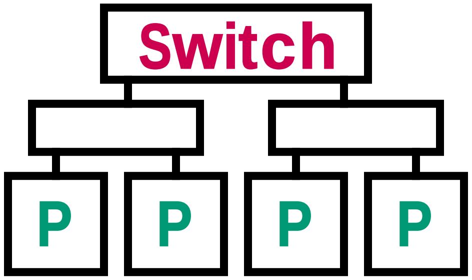


- Advantages
  - \+ Avoids broadcast → scalable
  - \+ Few interconnect restrictions
- Disadvantage
  - \- Directory state
  - \- Slow cache-to-cache transfers (3-hops)
- Example: Alpha 21364 - directory protocol with 2D torus

GAINS SCALABILITY AT THE COST OF SLOW 3-HOP TRANSACTIONS

Modern SMPs

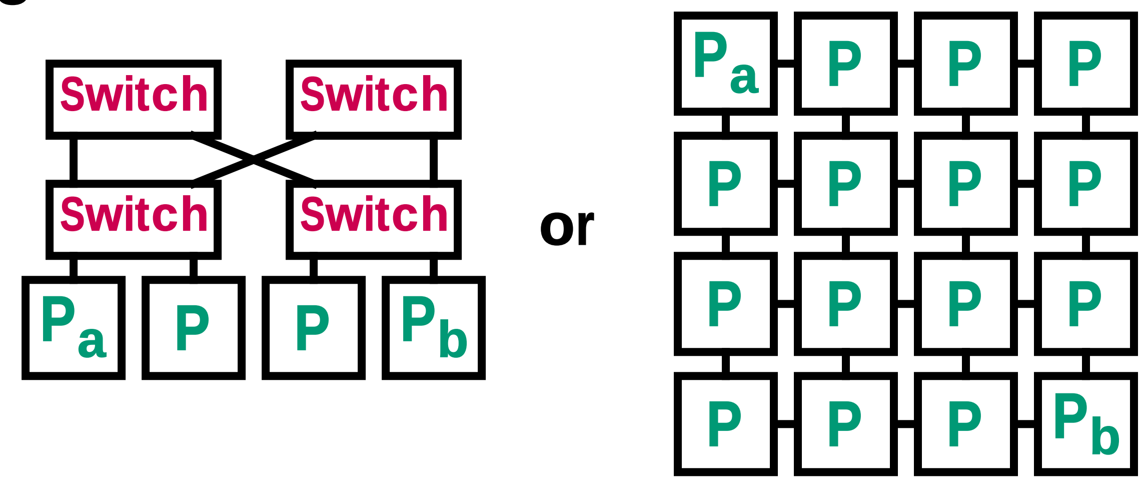
- Many enhancements
  - Multiple buses
  - Pipelined broadcast tree with point-to-point links
- Commercially successful, few academic papers
- Challenges
  - 'Logical bus' → synchronous broadcast
  - Global snoop responses
  - Arbitration & flow control
- Example: Sun E10000 - 64 processors
  130 ASICs for interconnect



SMPs IMPOSE INTERCONNECT RESTRICTIONS

Extending Snooping

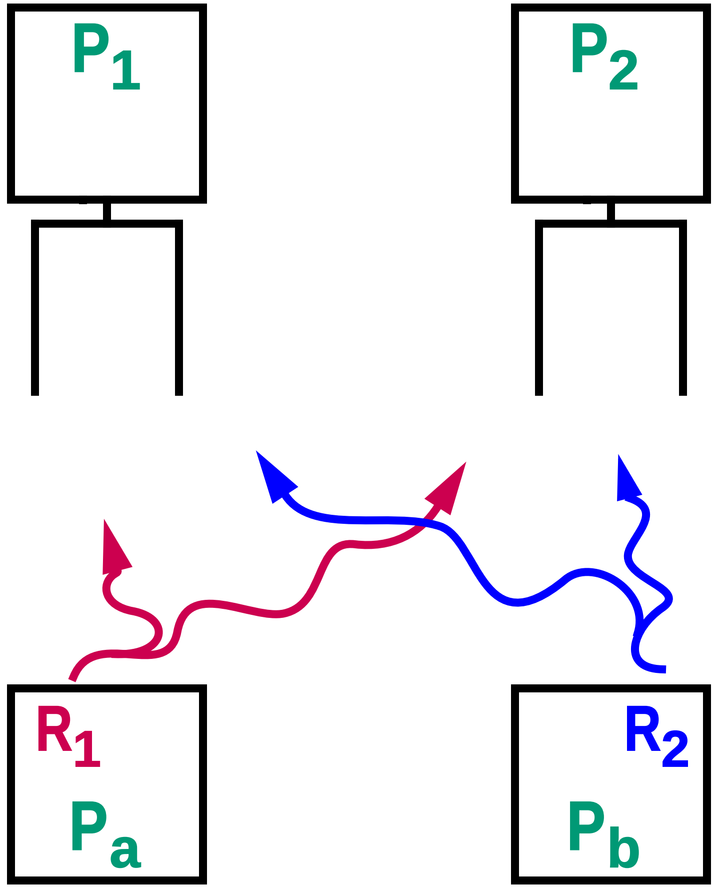
- Key requirements
  - **Total order**
  - Broadcast
- Relax other requirements
  - No synchronous interconnect
  - Arbitrary topology (direct or indirect)
  - No snoop responses
  - No global arbitration



PROVIDE TOTAL ORDER WITH FEWER INTERCONNECT RESTRICTIONS

Timestamp Snooping

- **Goal:** Create a logical total order



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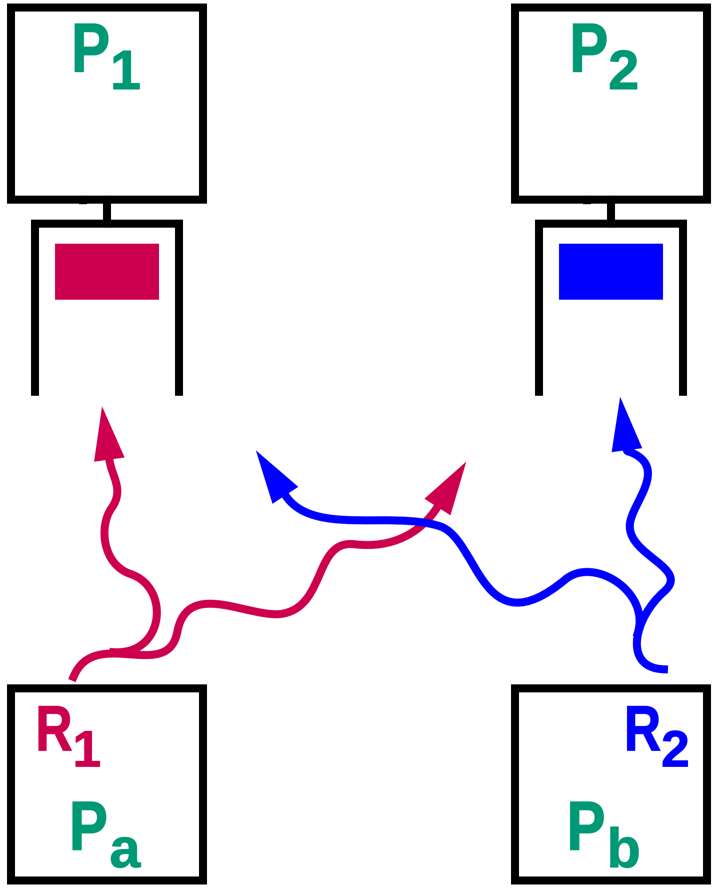

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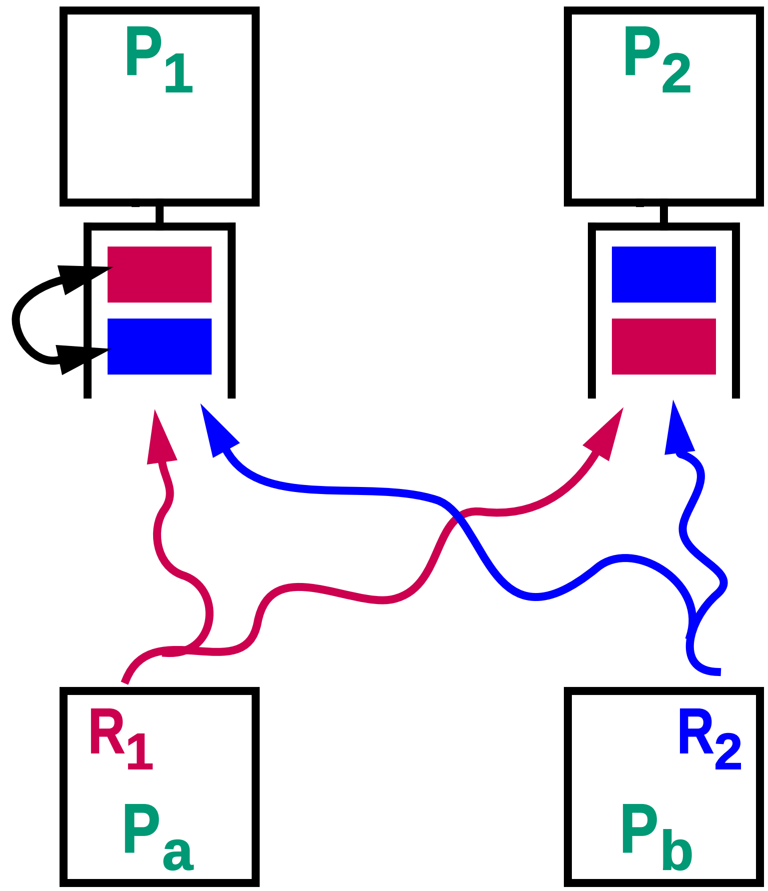

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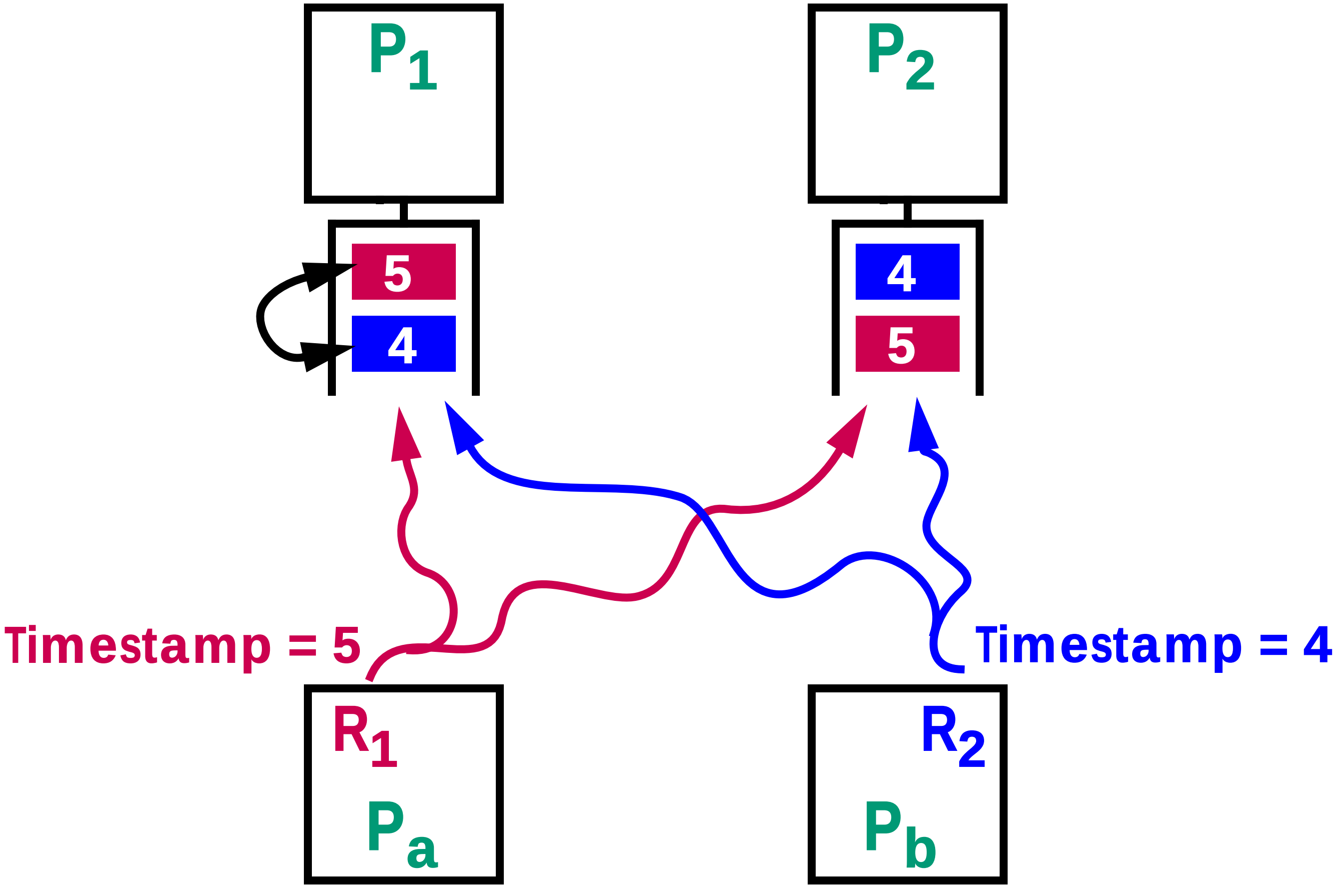

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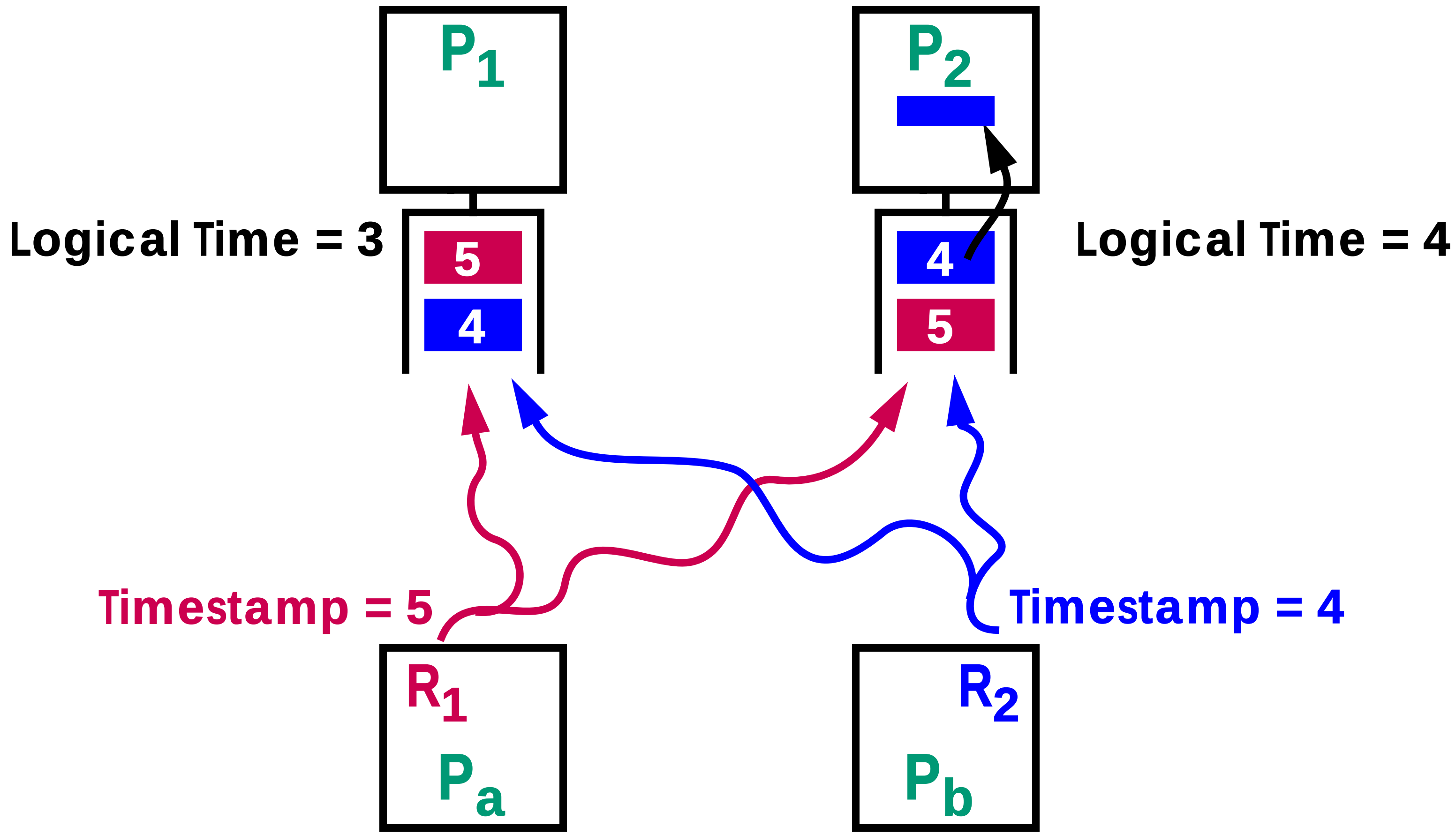

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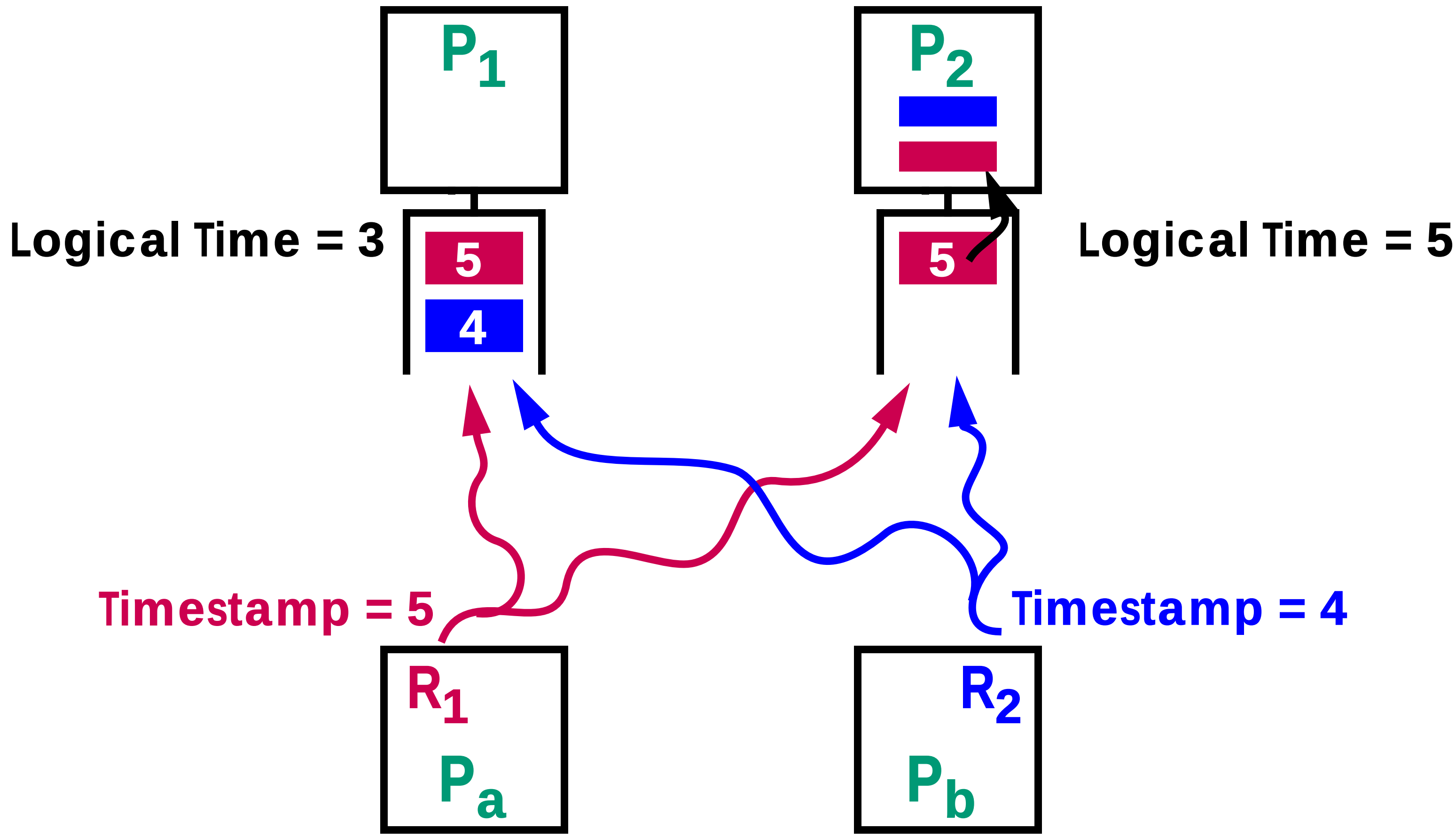

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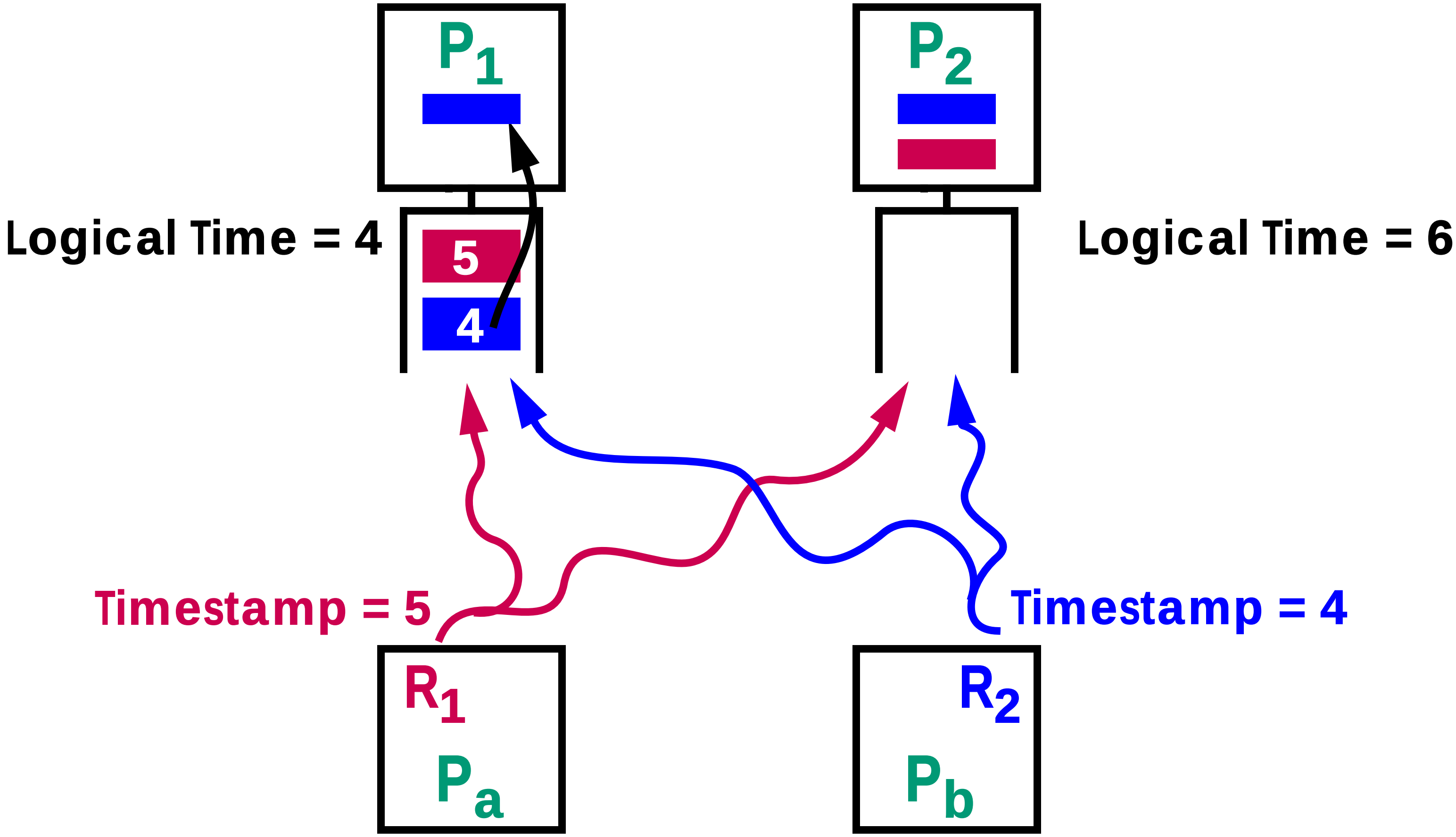

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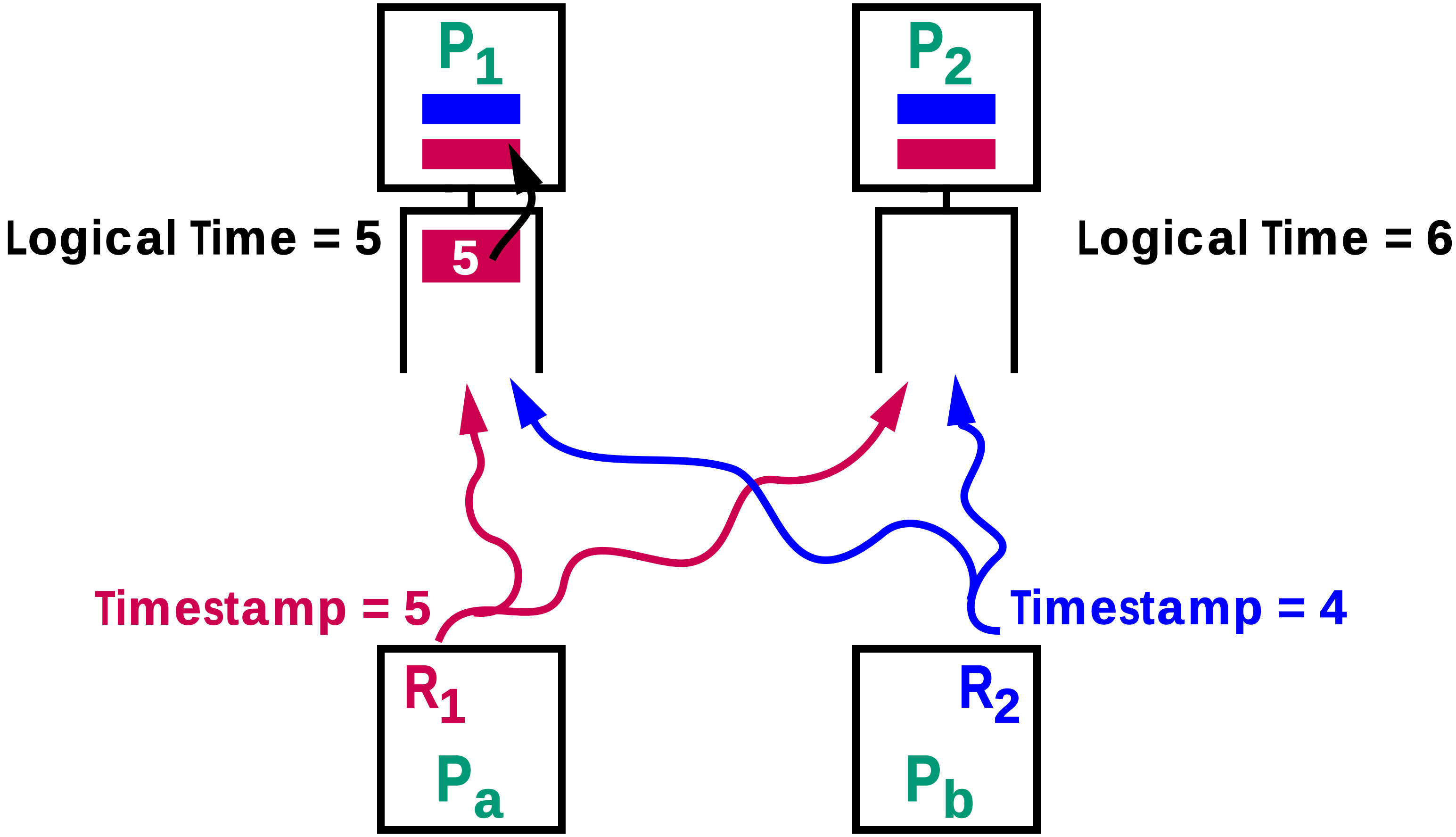

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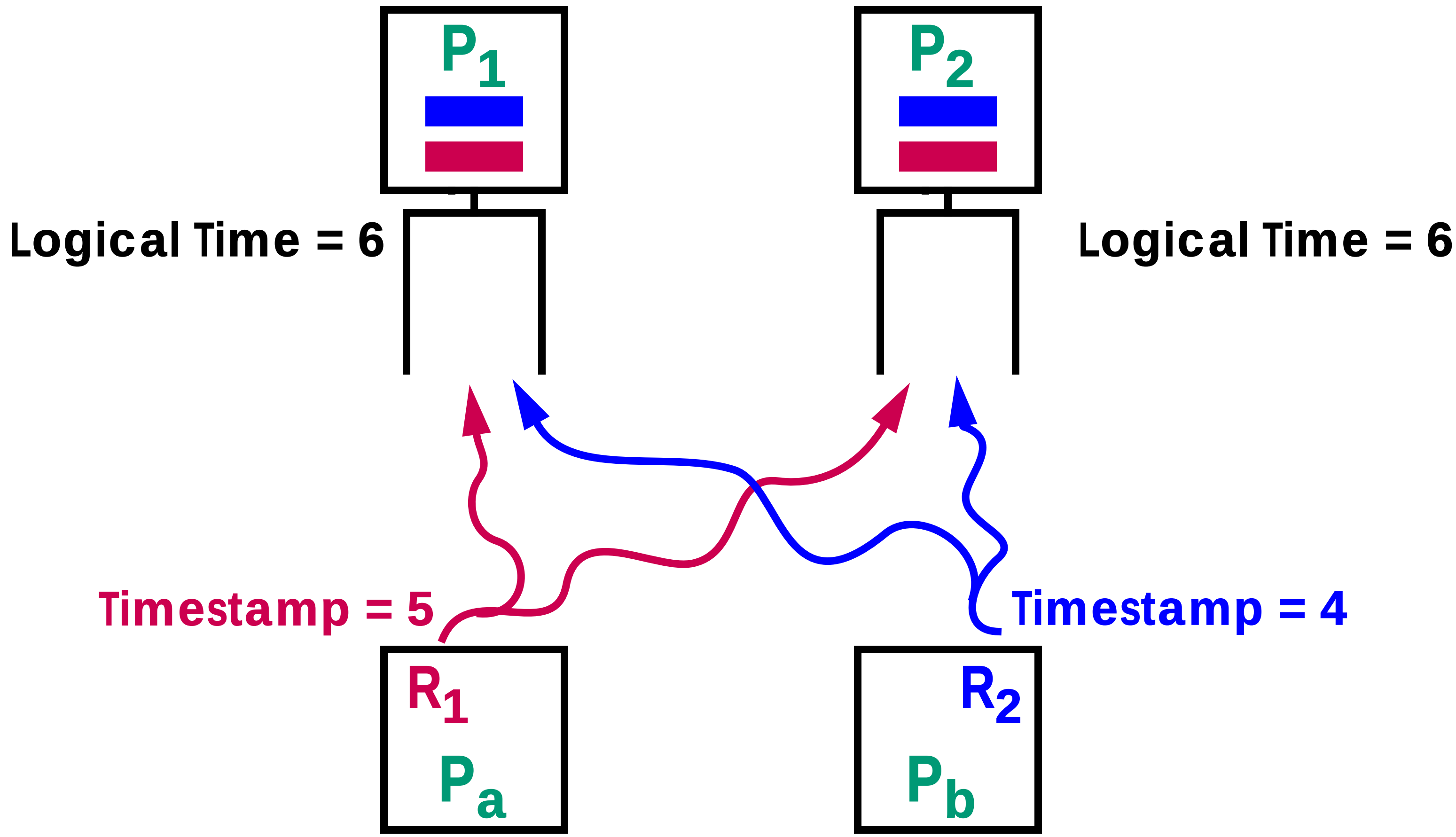
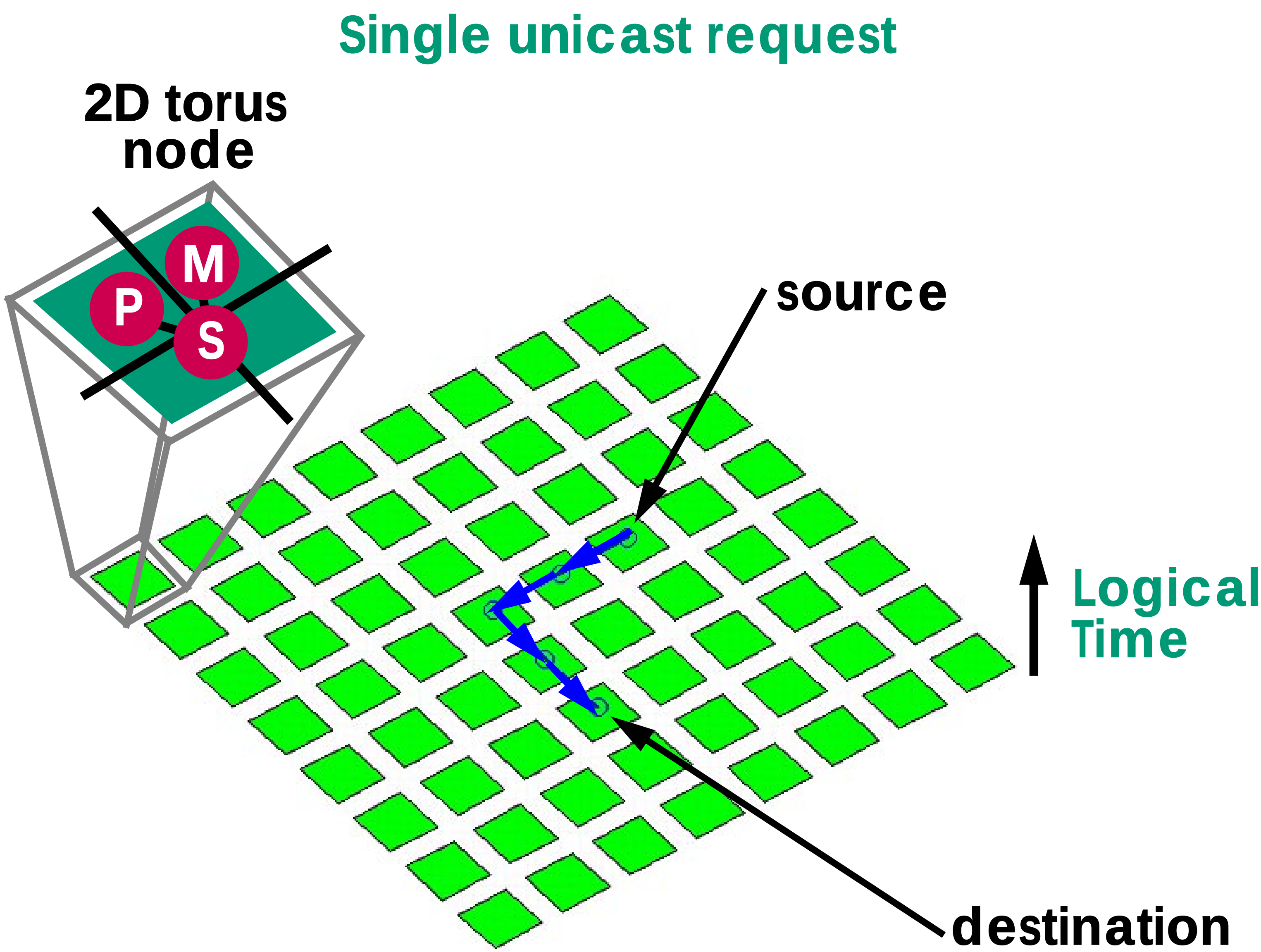


Logical Time

- Ordering Time (OT)
  - Arrival timestamp of request
  - Assign at source
  - Broadcast without regard to order
  - Re-order at the end-points
- Guarantee Time (GT)
  - Logical time base
  - Recursively maintained at switches
- Invariant
  - Messages delivered while $OT_{request} \geq GT_{destination}$

Uncontended Example



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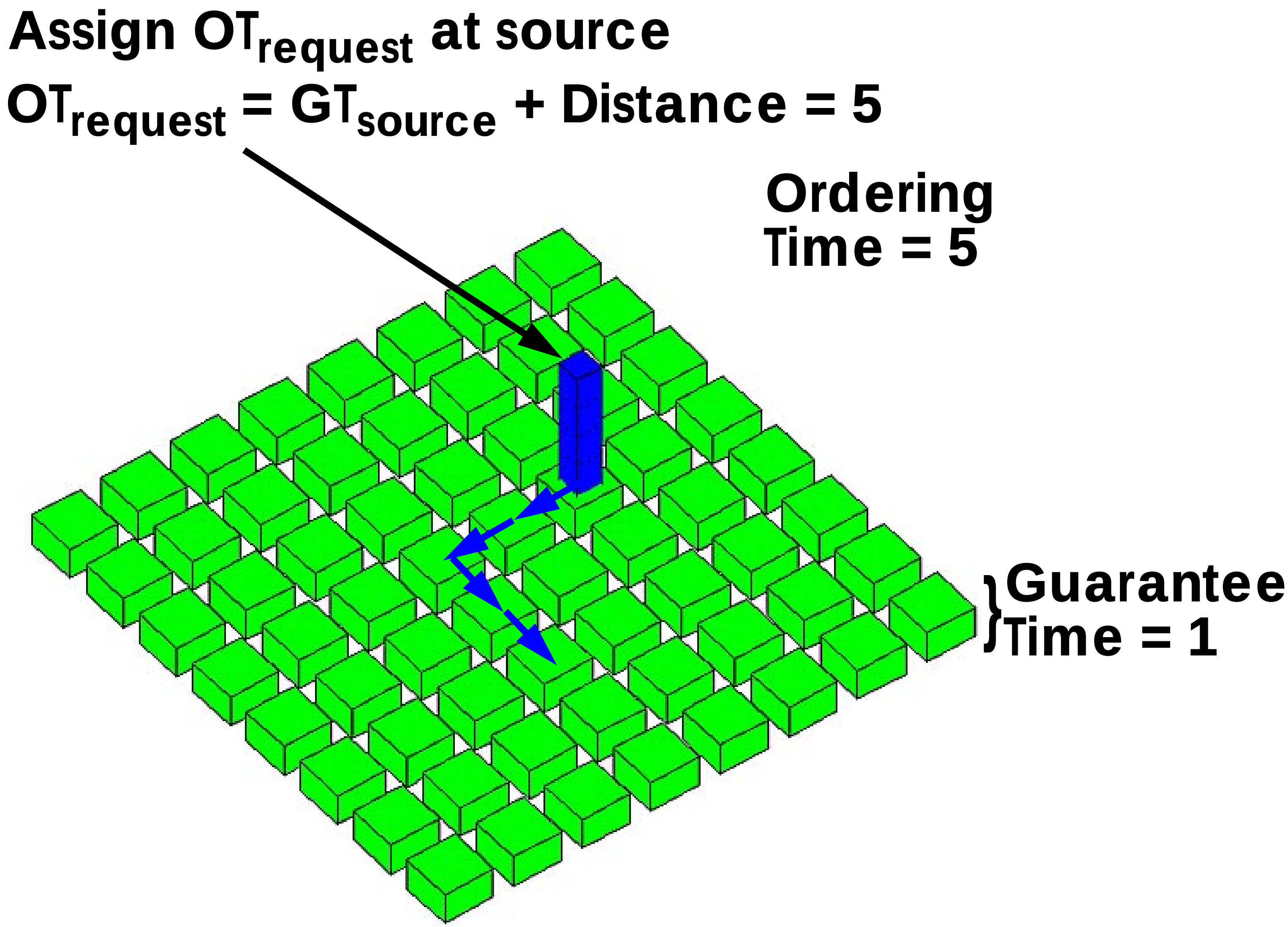

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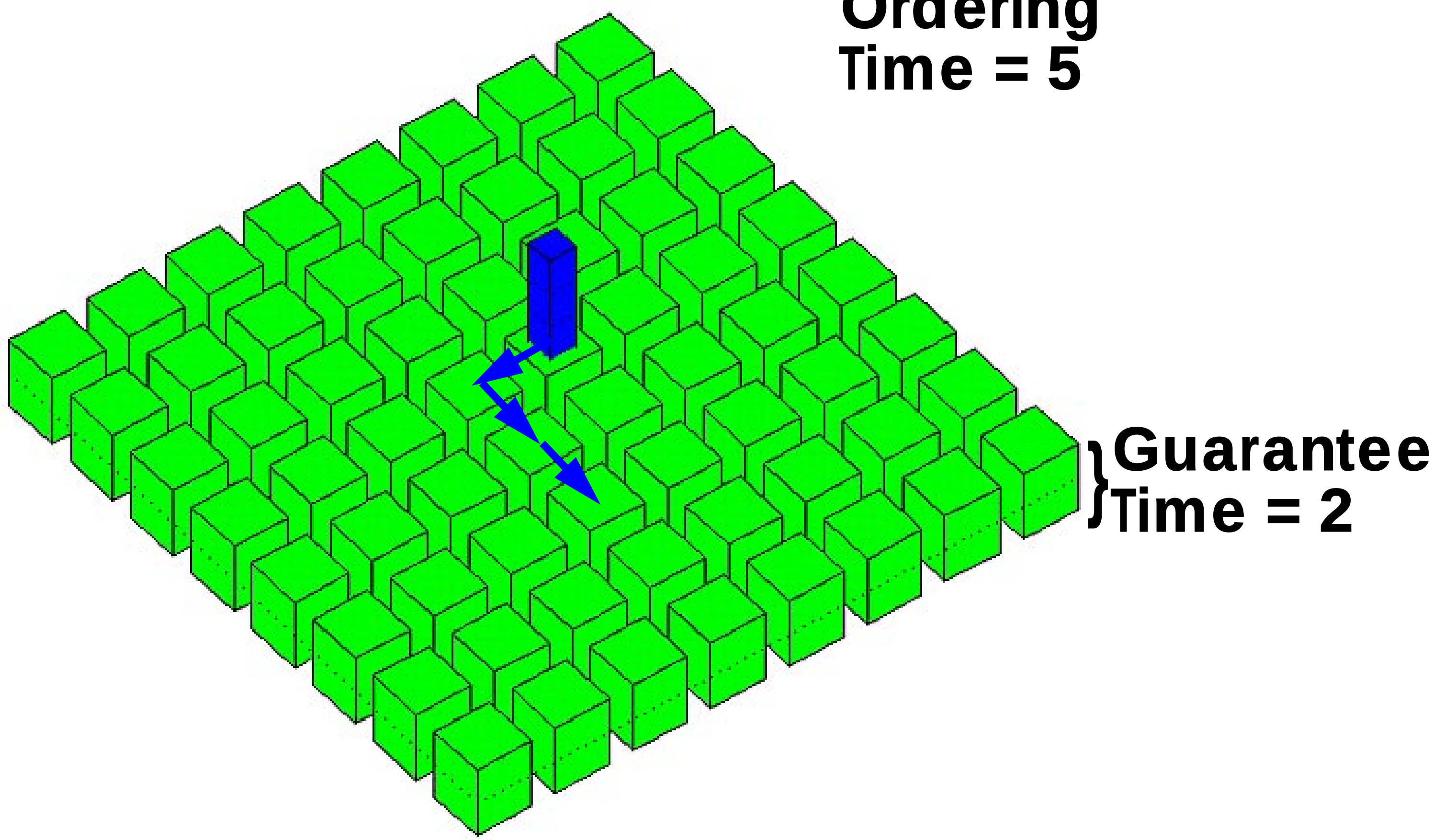

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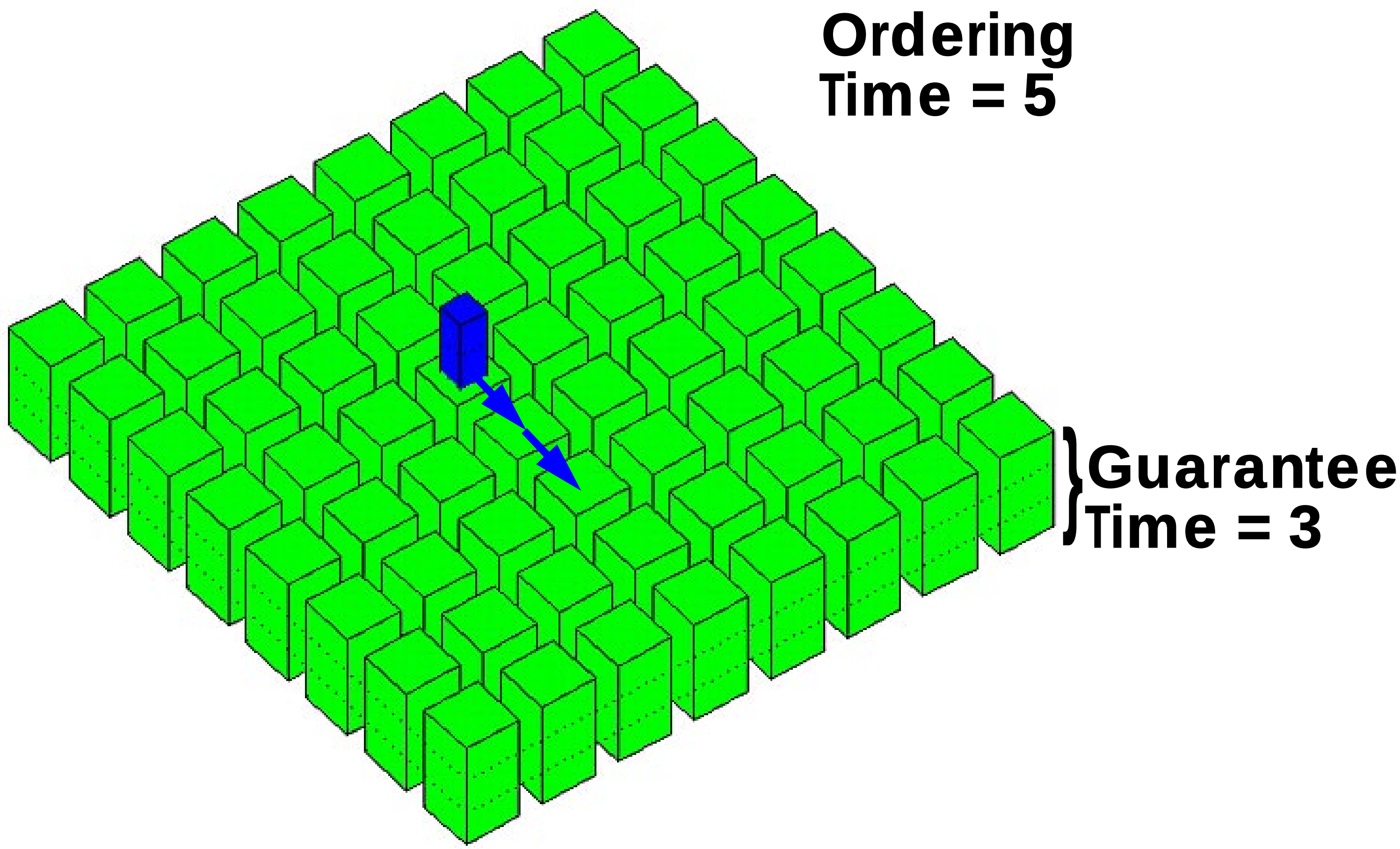

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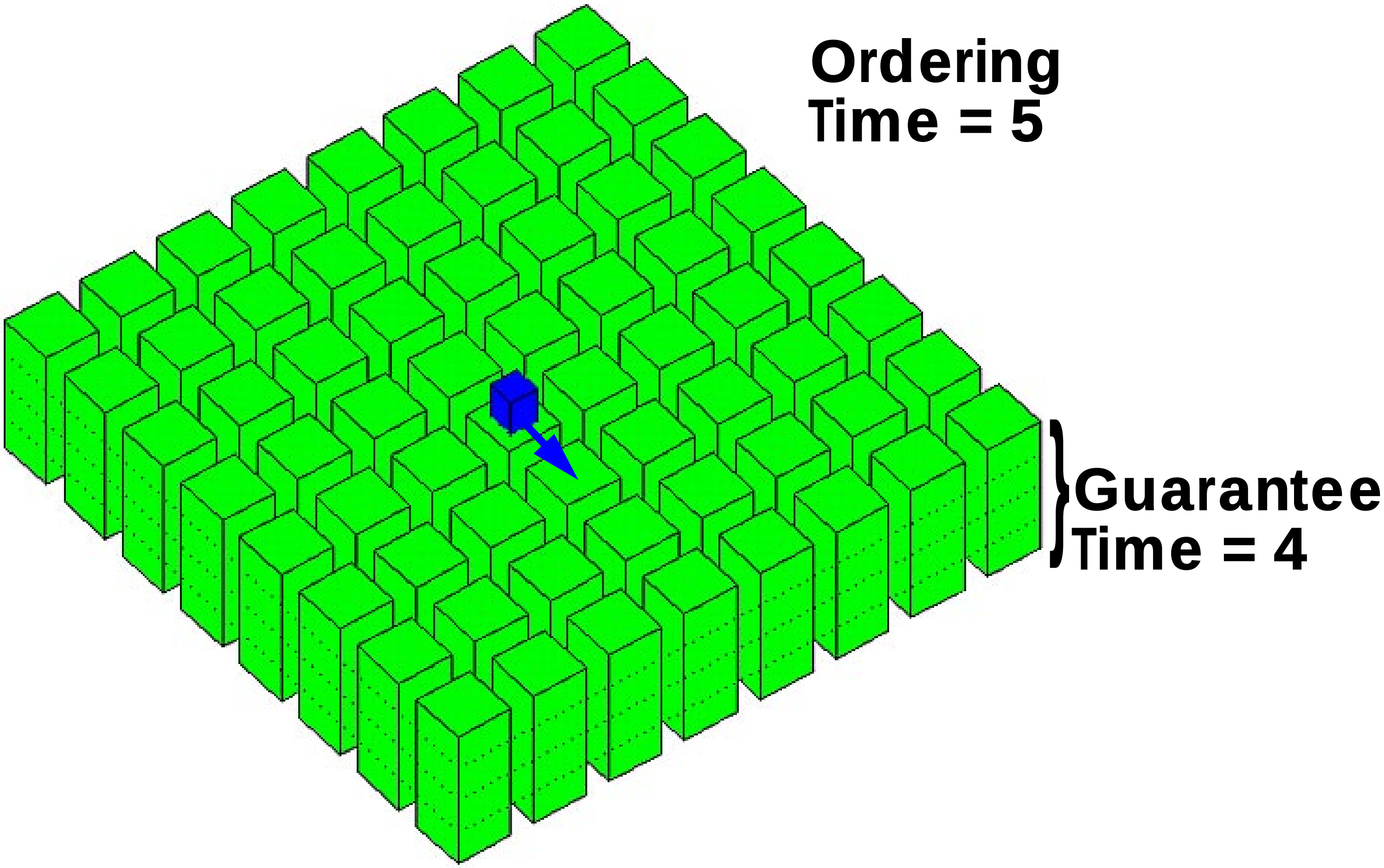

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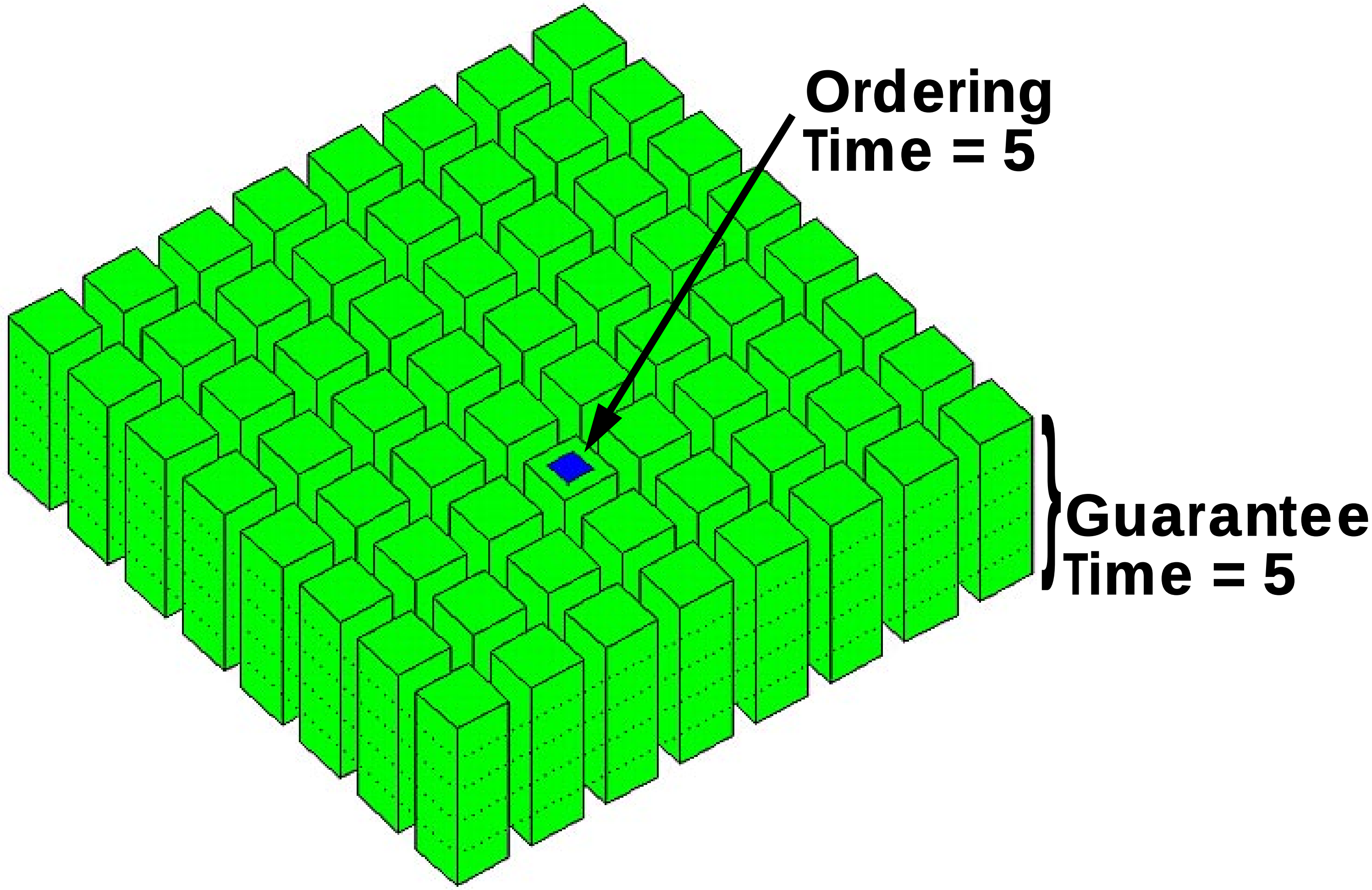
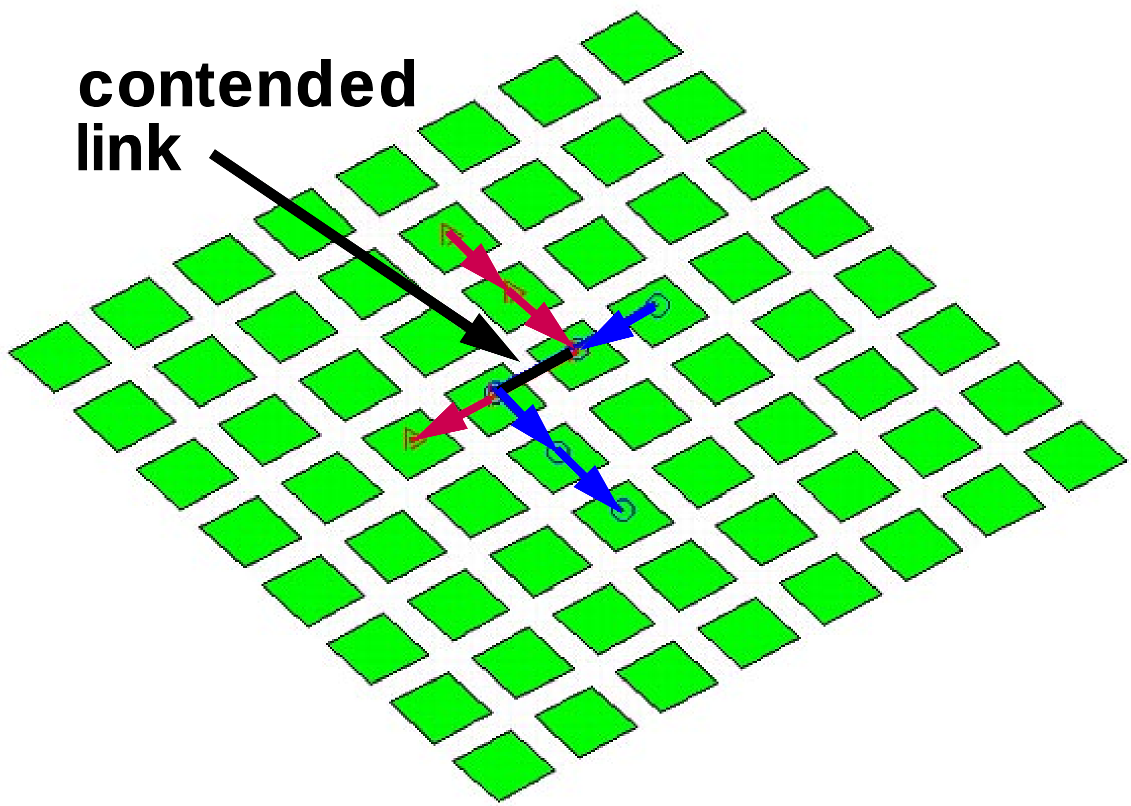


Interconnect Contention

- **Invariant**
  - **Requests delivered while $OT_{request} \geq GT_{destination}$**
- **No contention**
  - **GTs always advance**
- **Contention**
  - **Recursively delay GTs to ‘warp time’**
  - **Prevent requests from being *late***

Contention Example

Two request example



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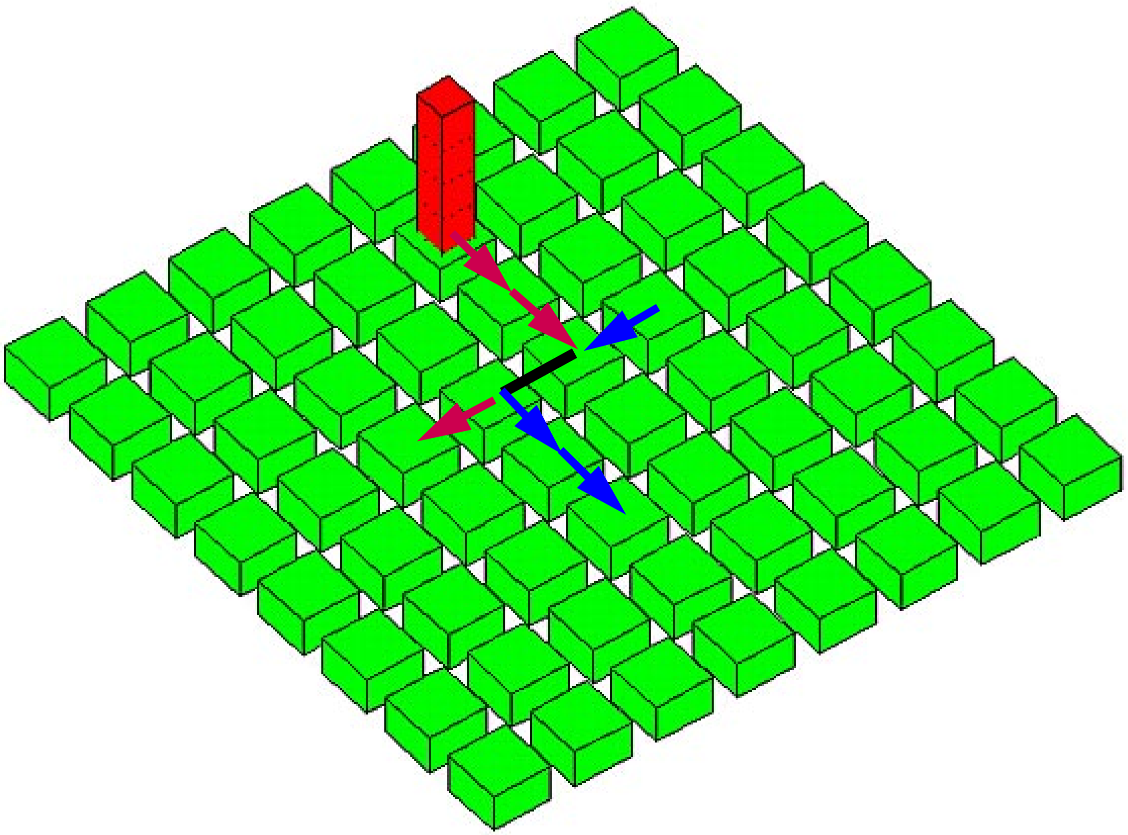

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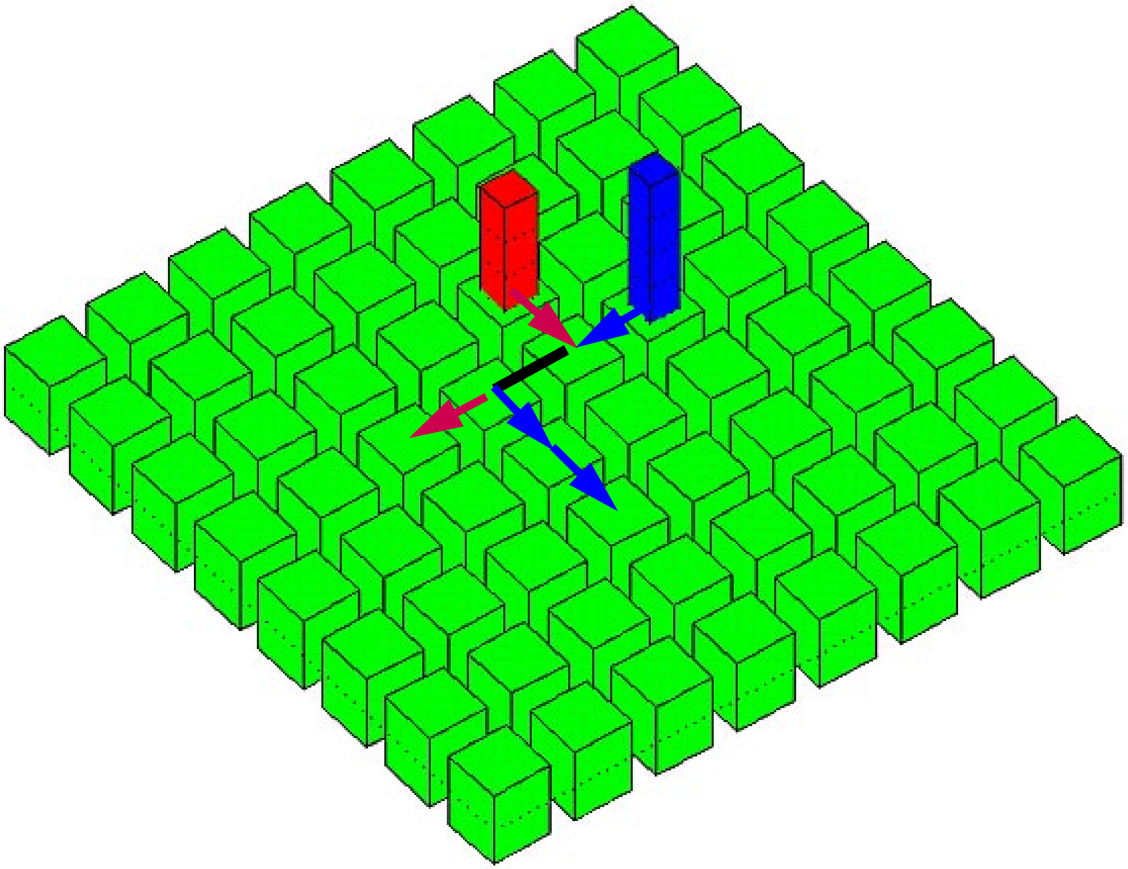

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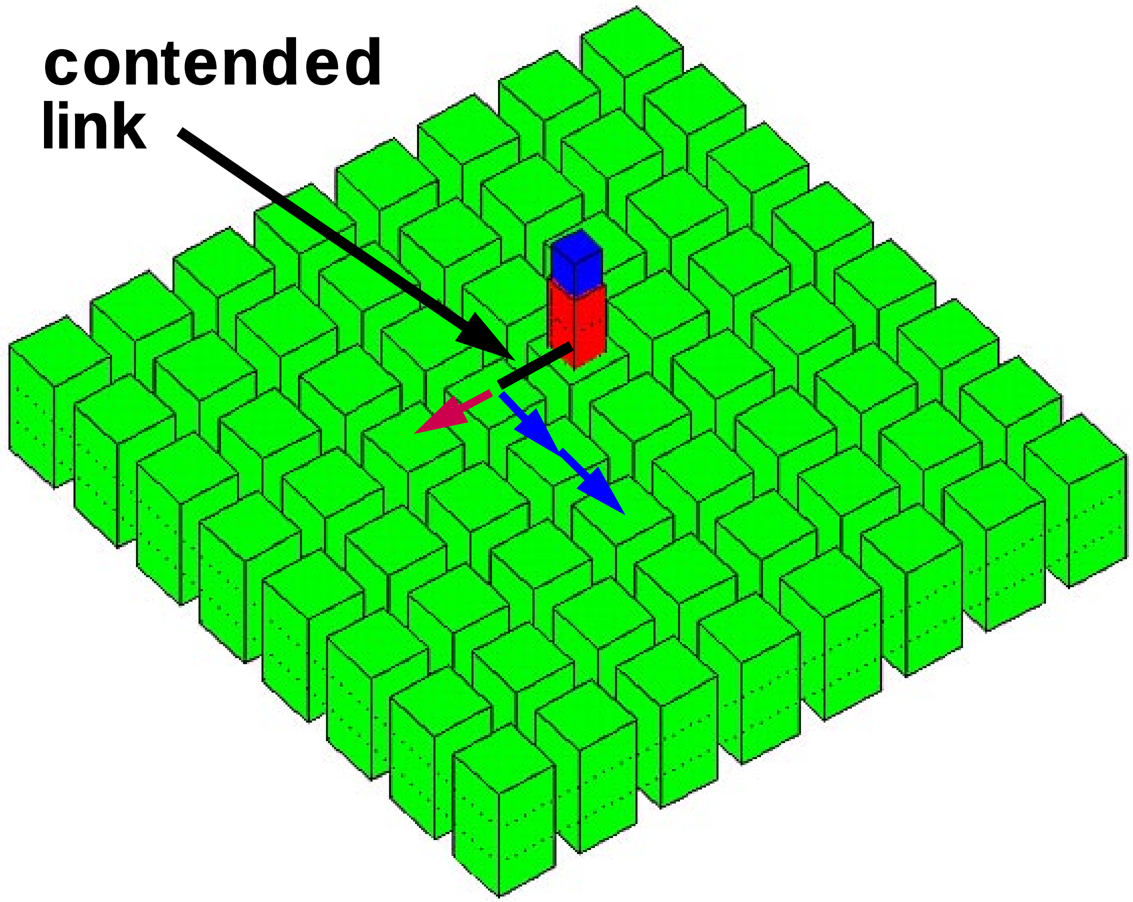

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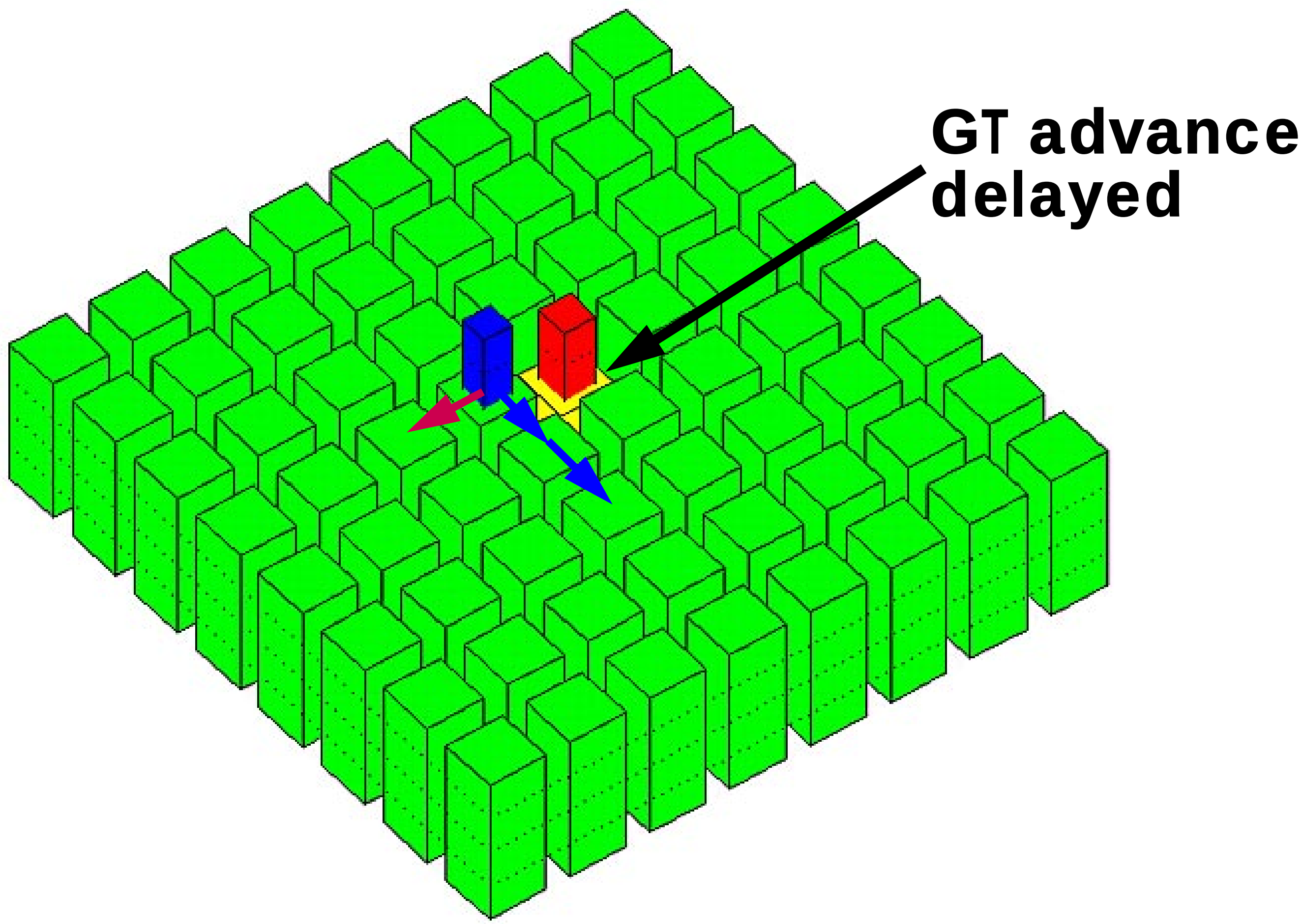

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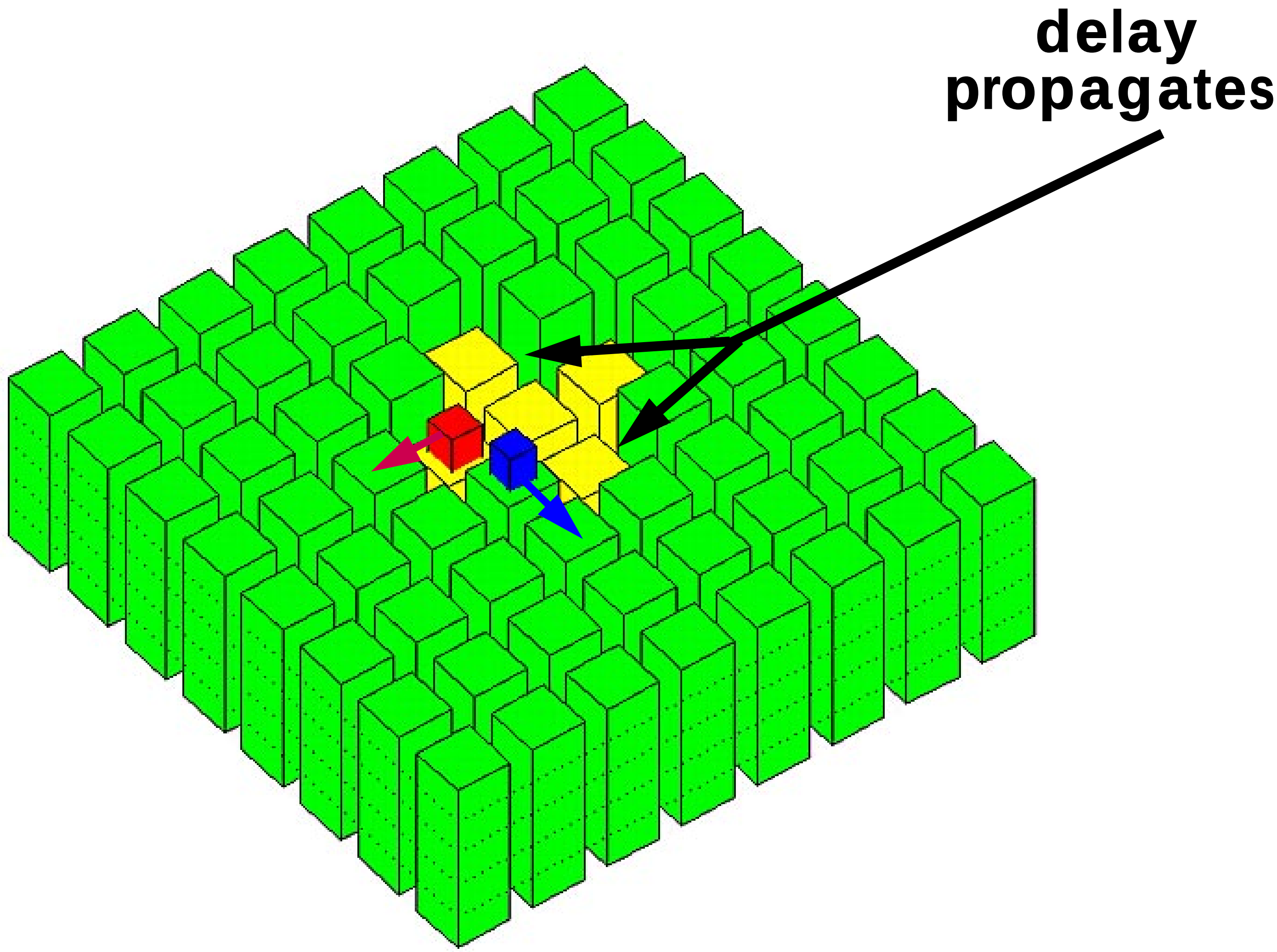

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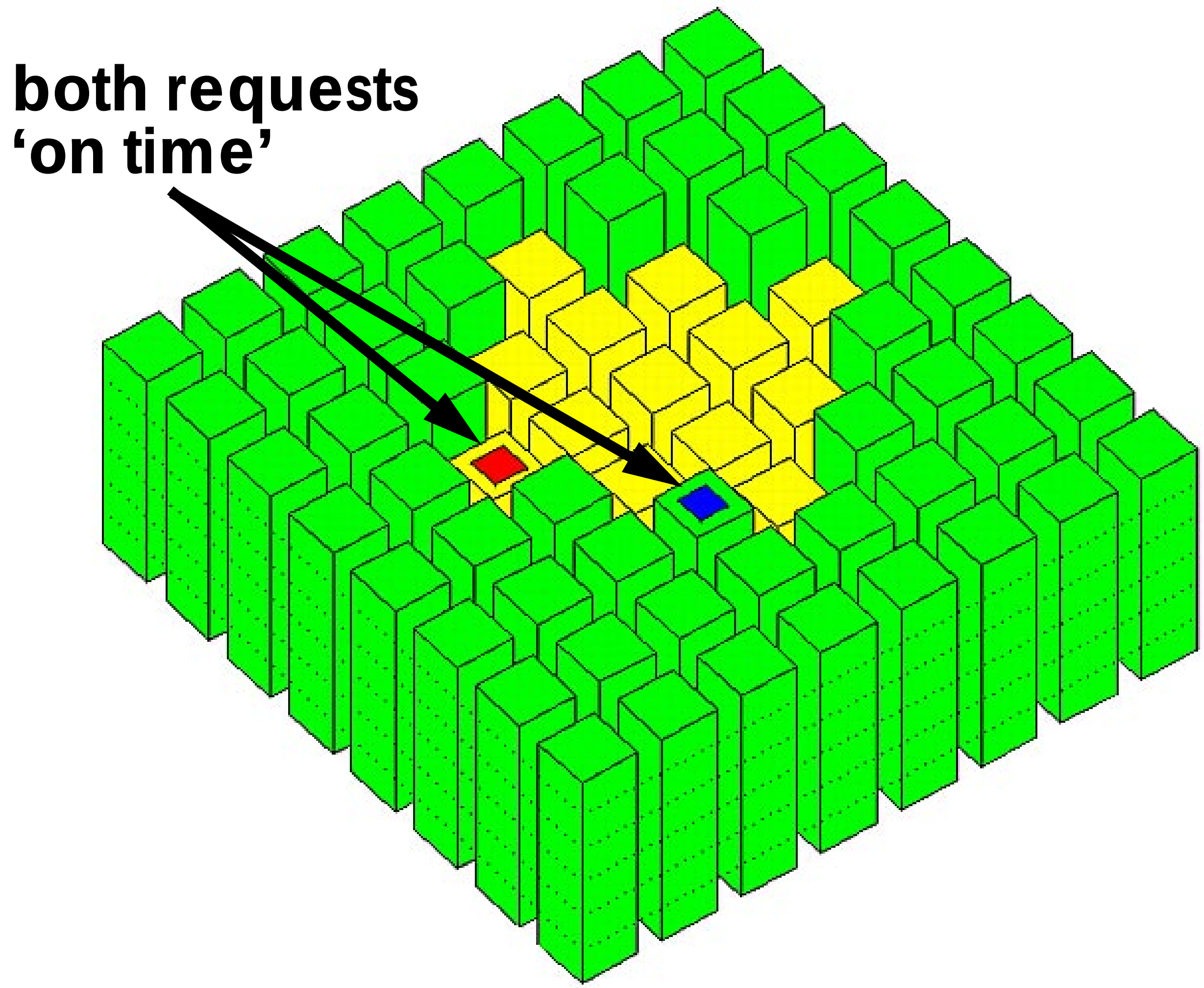

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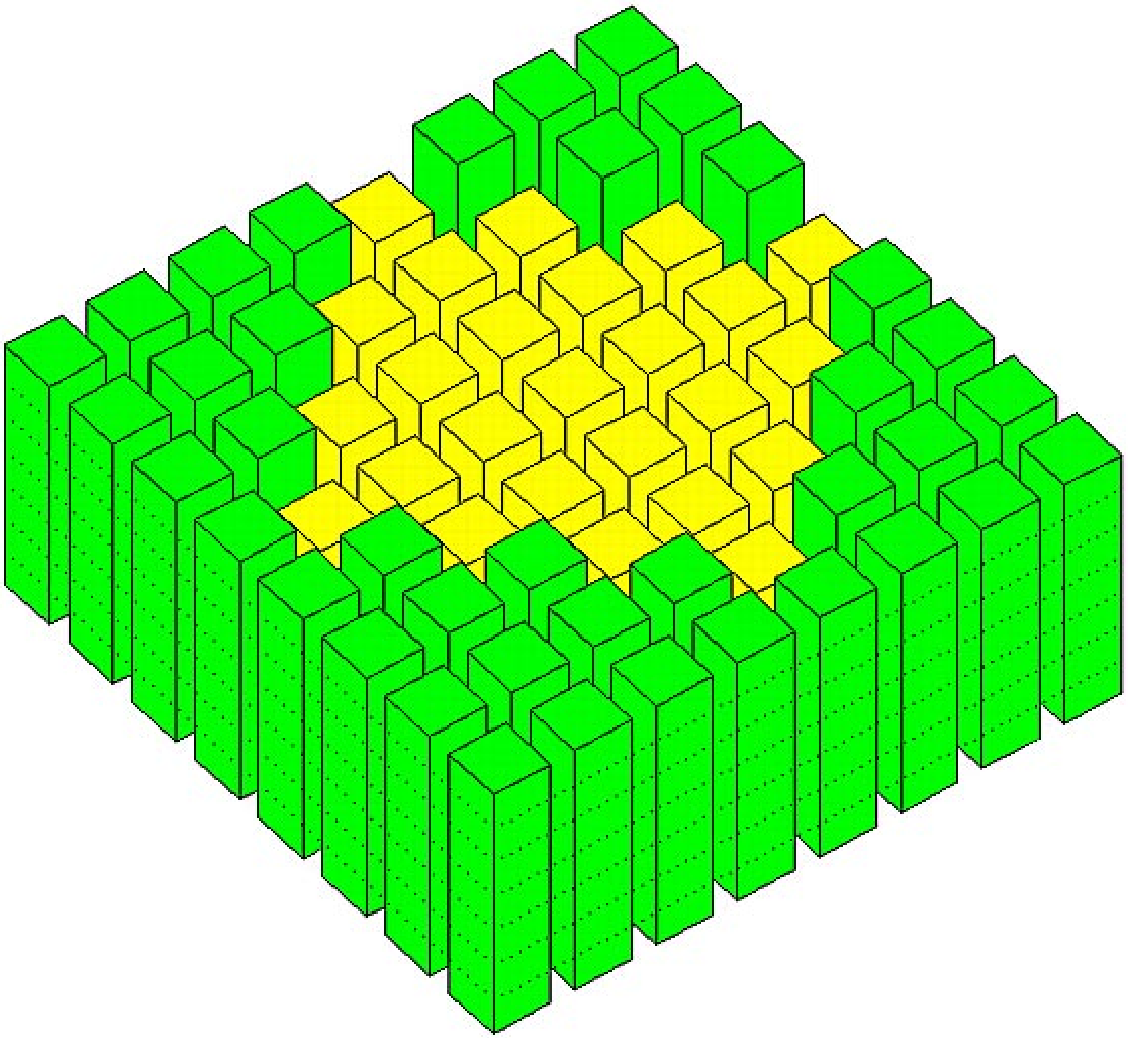

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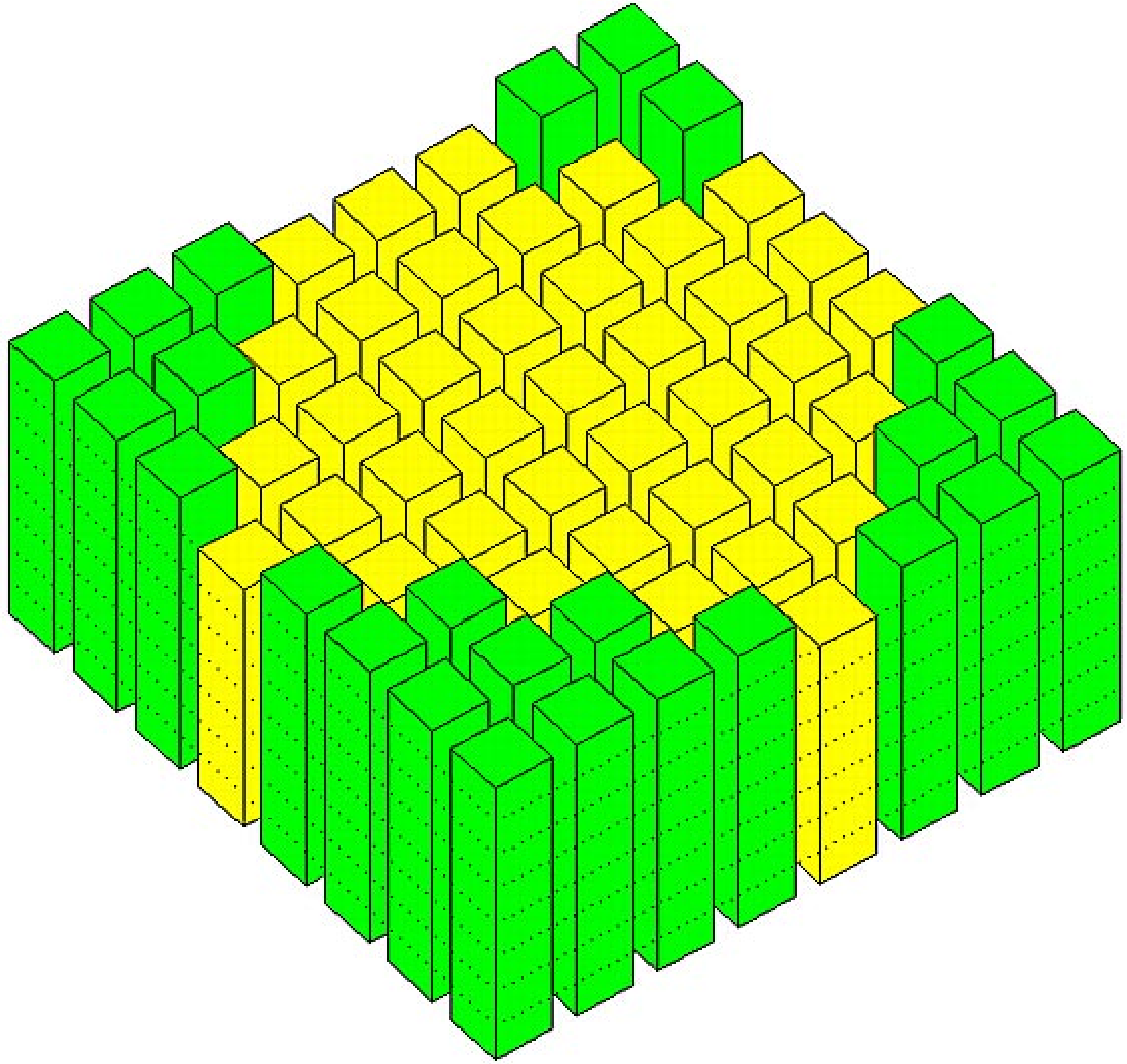

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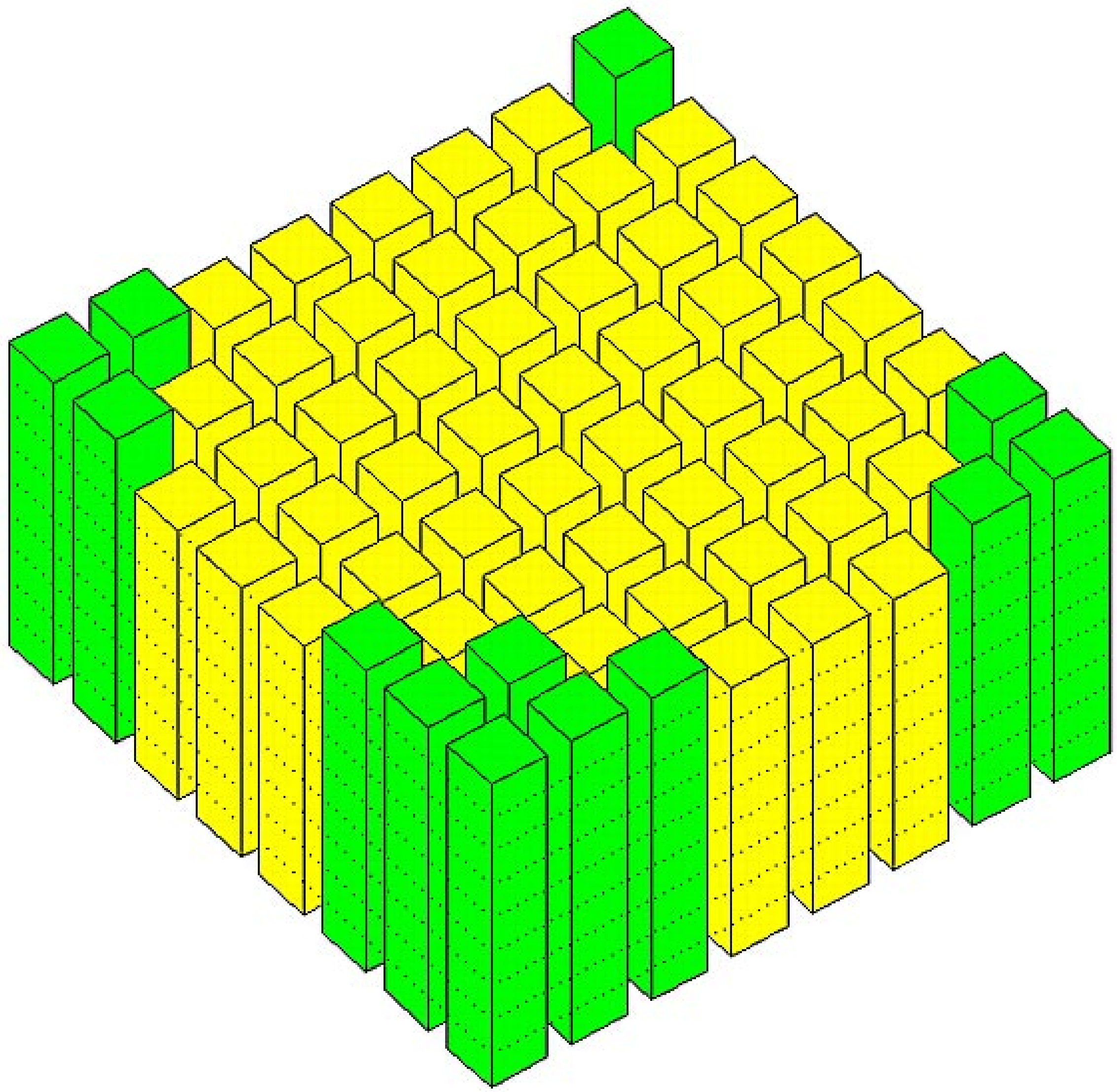

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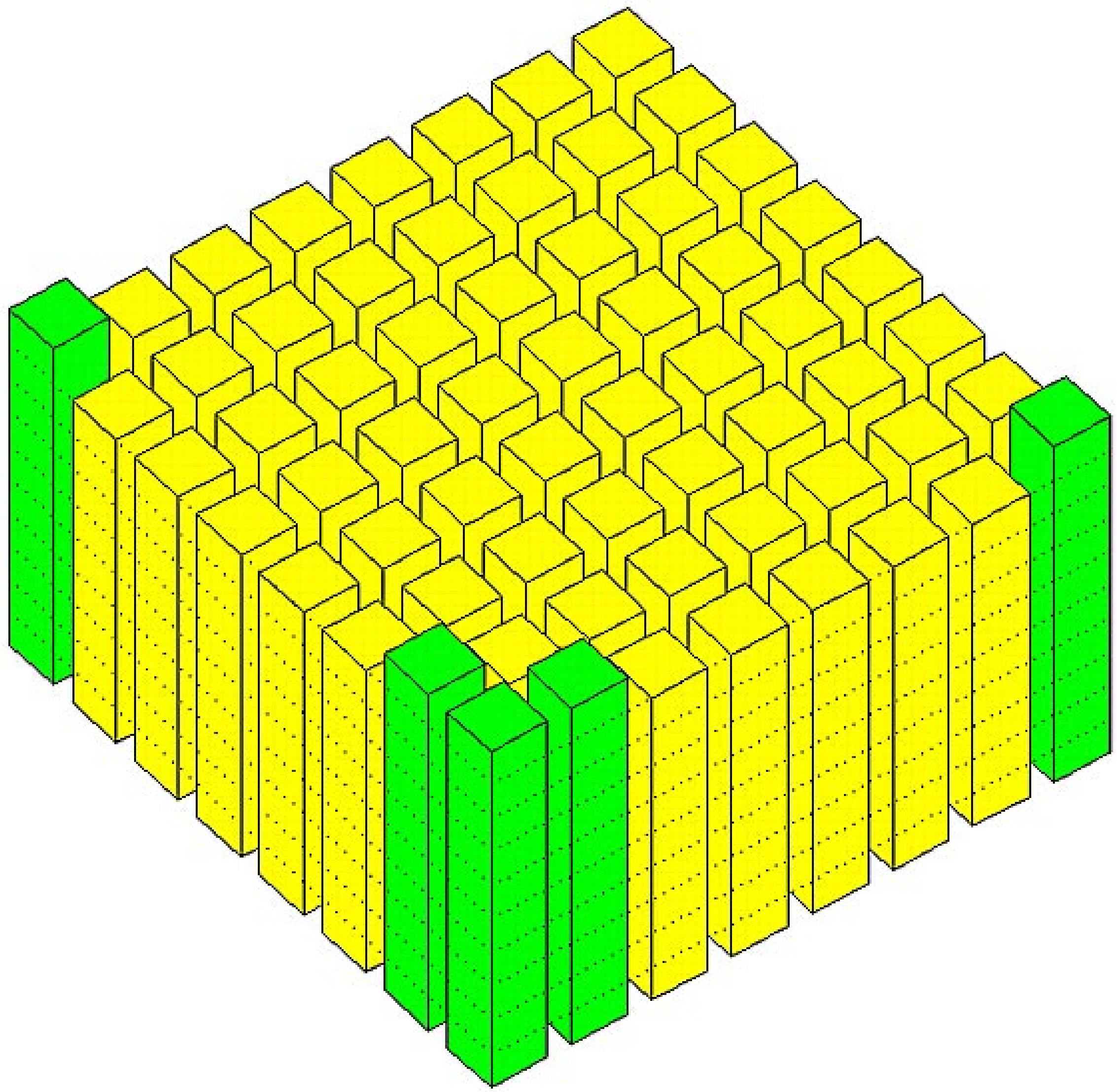

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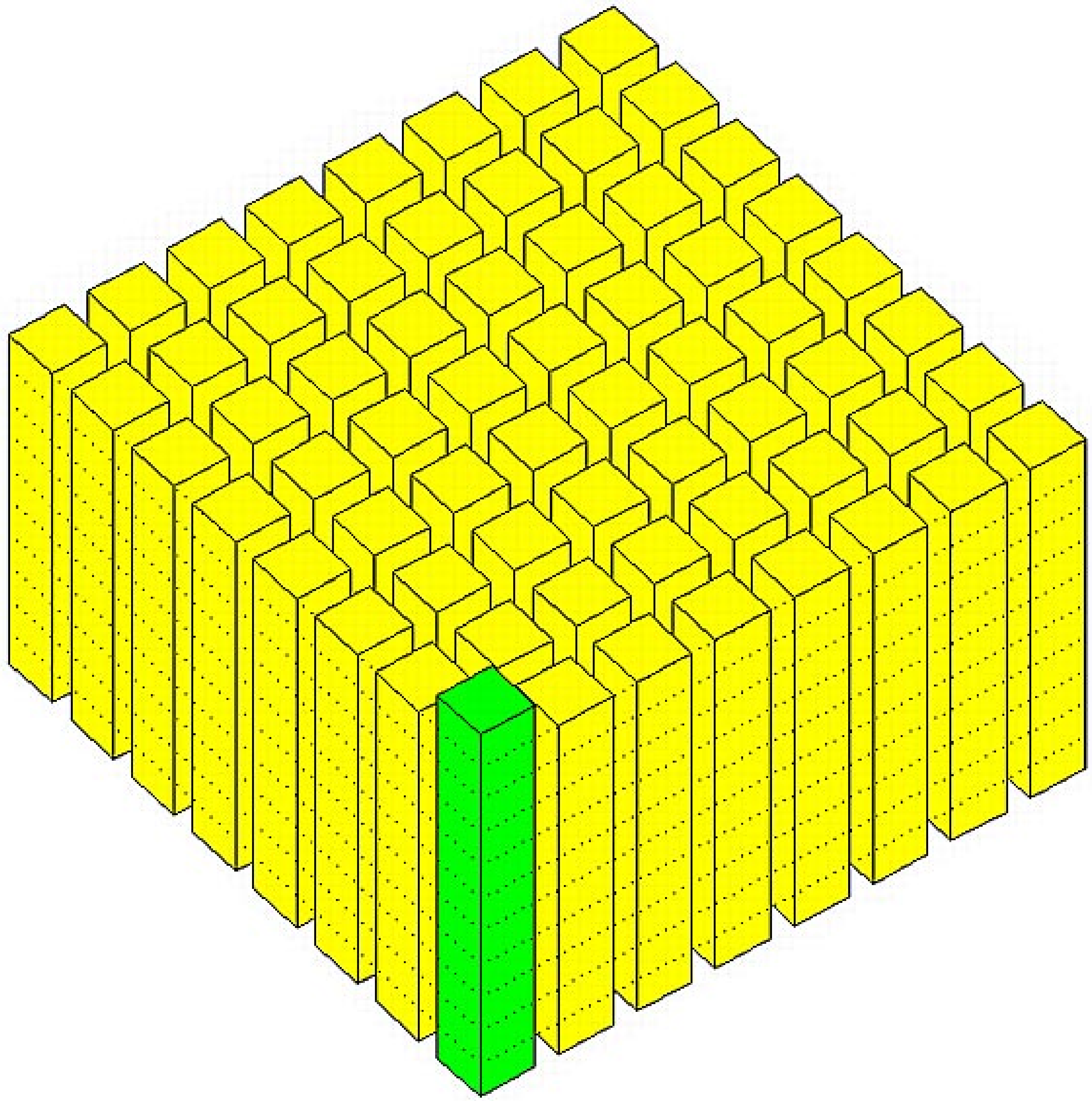

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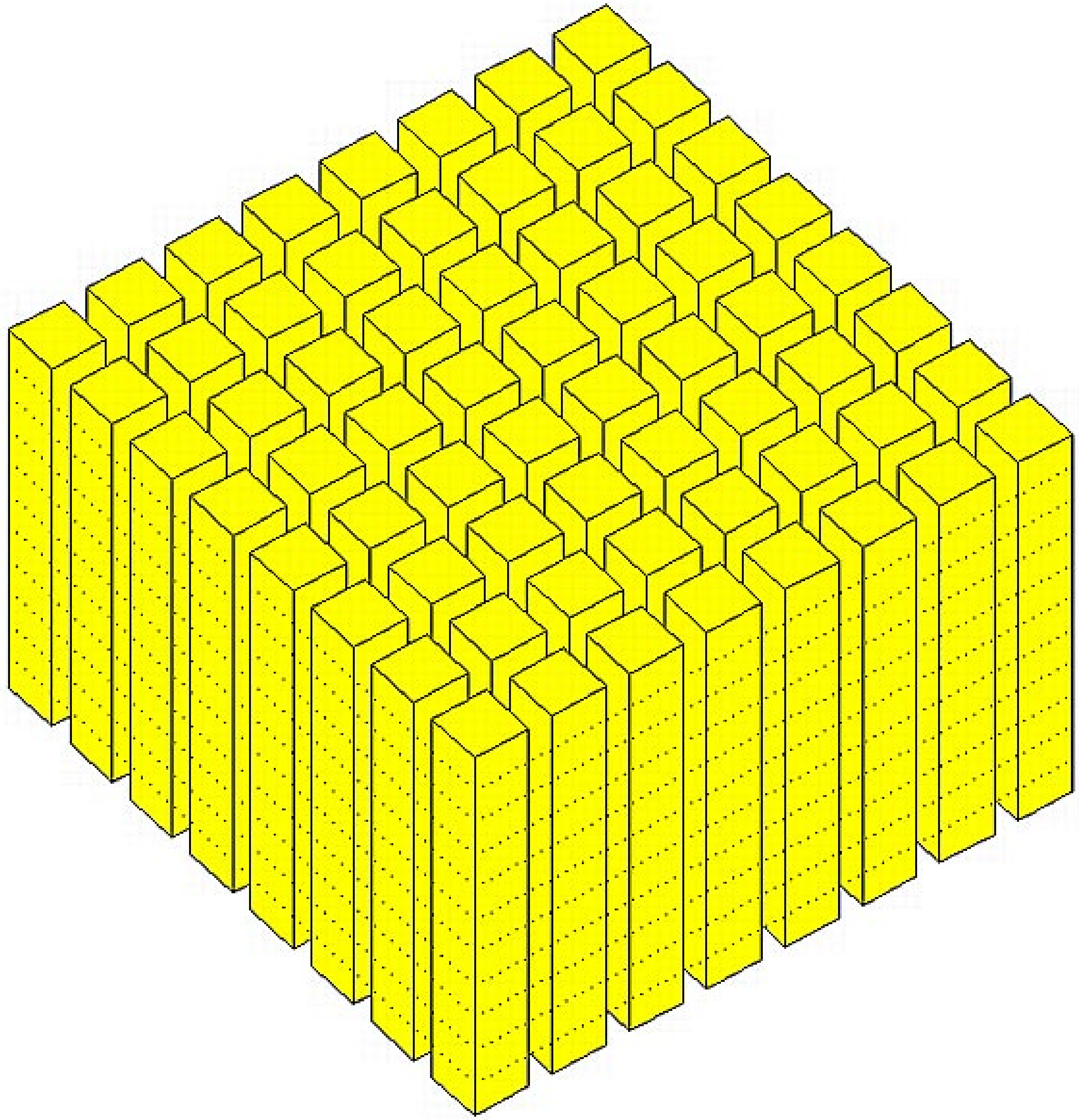
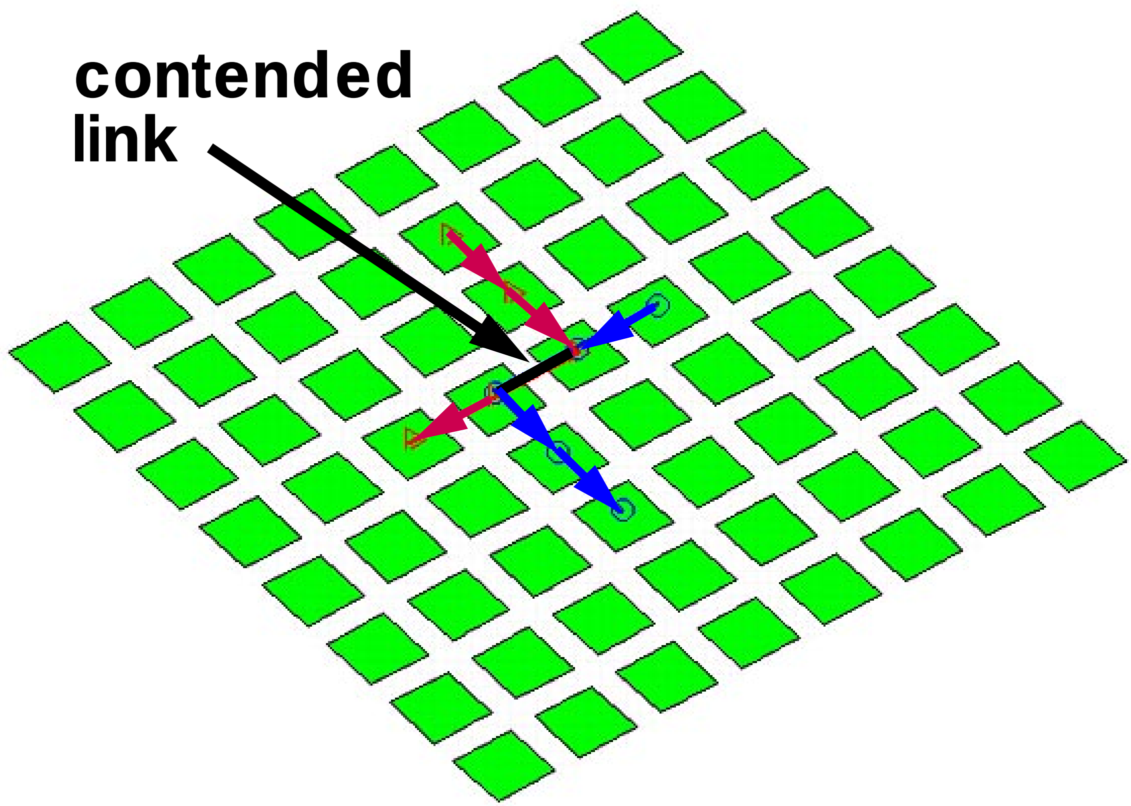


Adding Slack

- Contention
  - GTs delayed
  - Can delay processing of other requests
  - Recursively propagates
- Contention is common
  - Avoid delaying GTs in moderate contention
  - Add *slack* to initial OTs
  - Slack: extra logical time to reach destination

Slack Example

Two requests with slack



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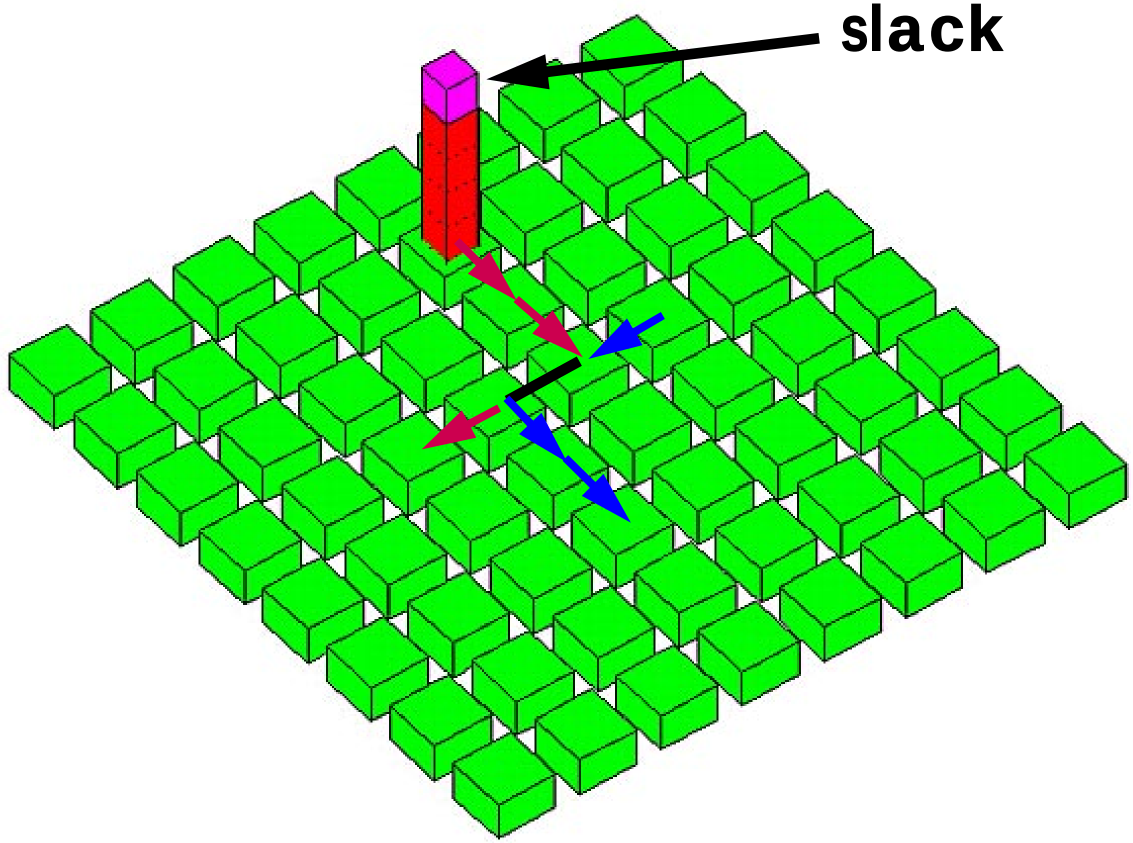

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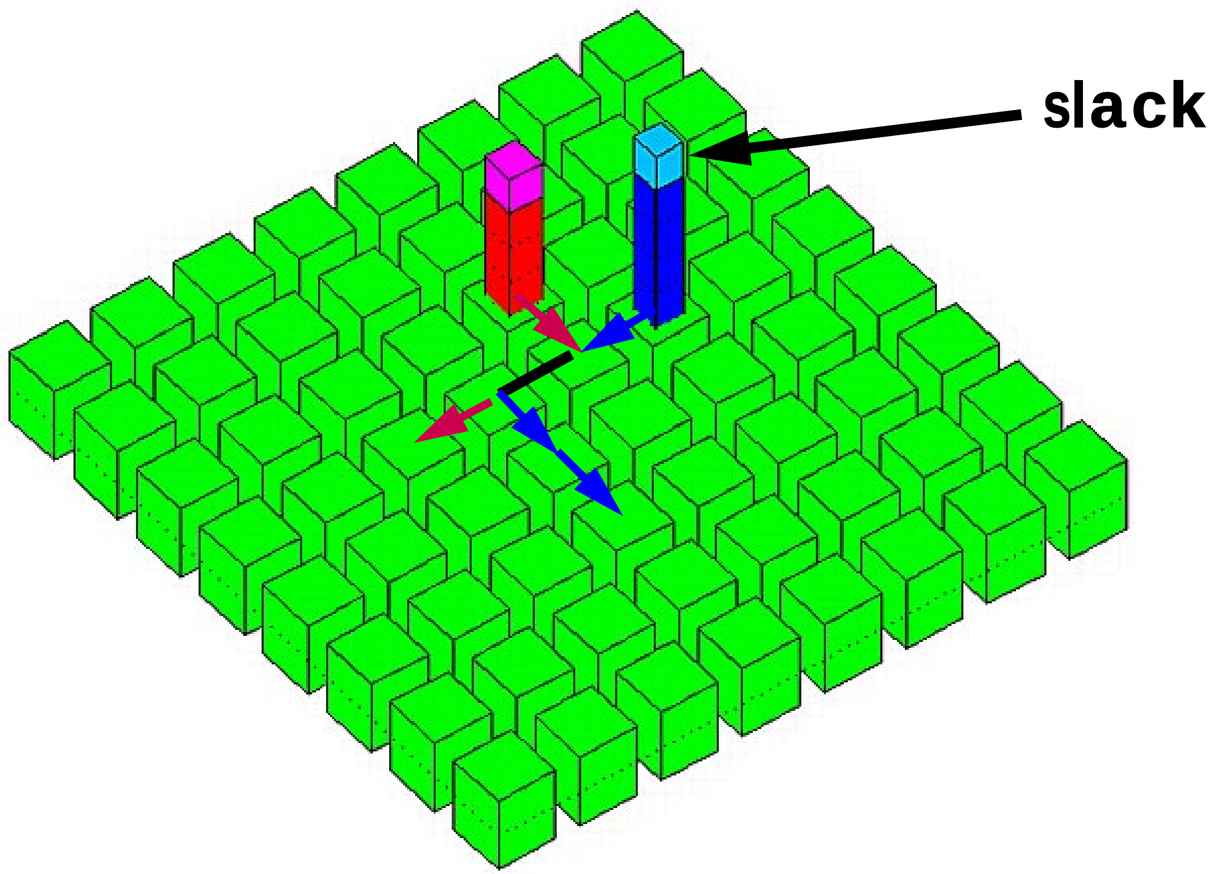

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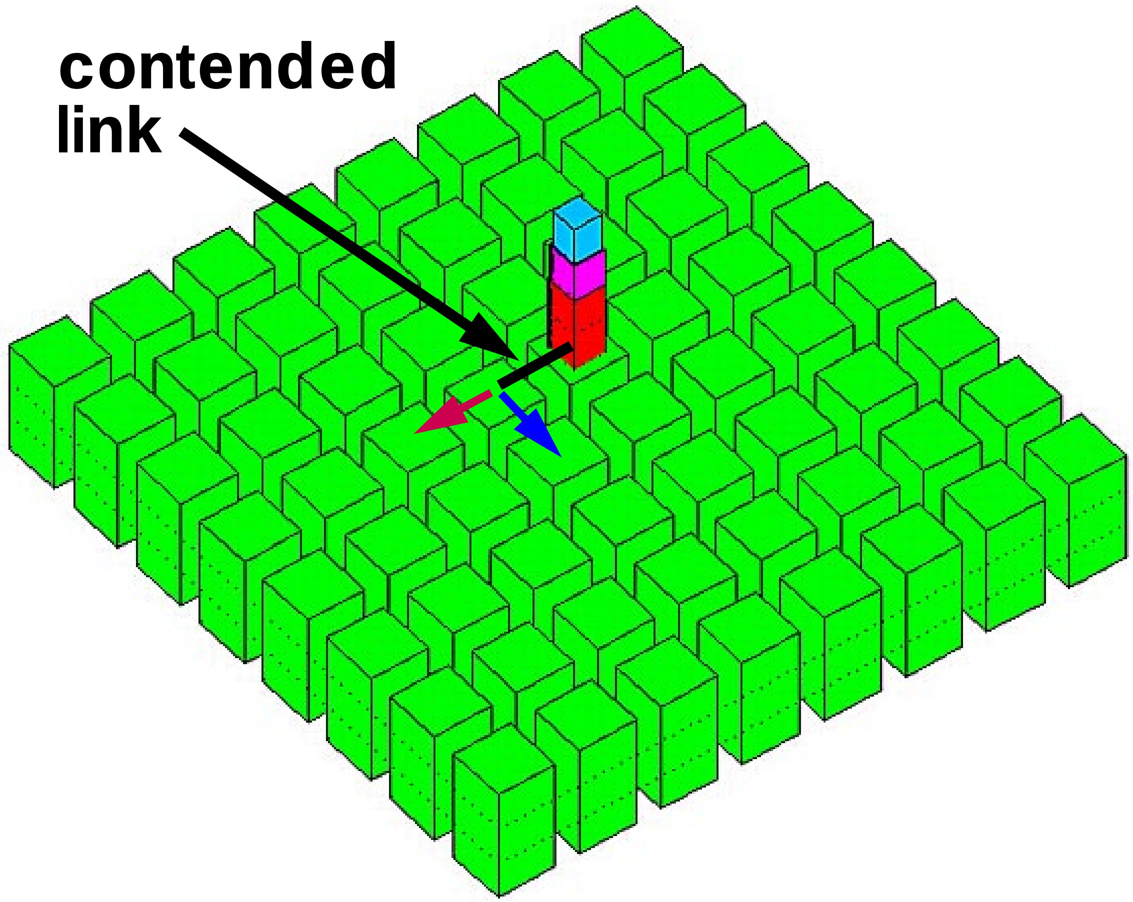

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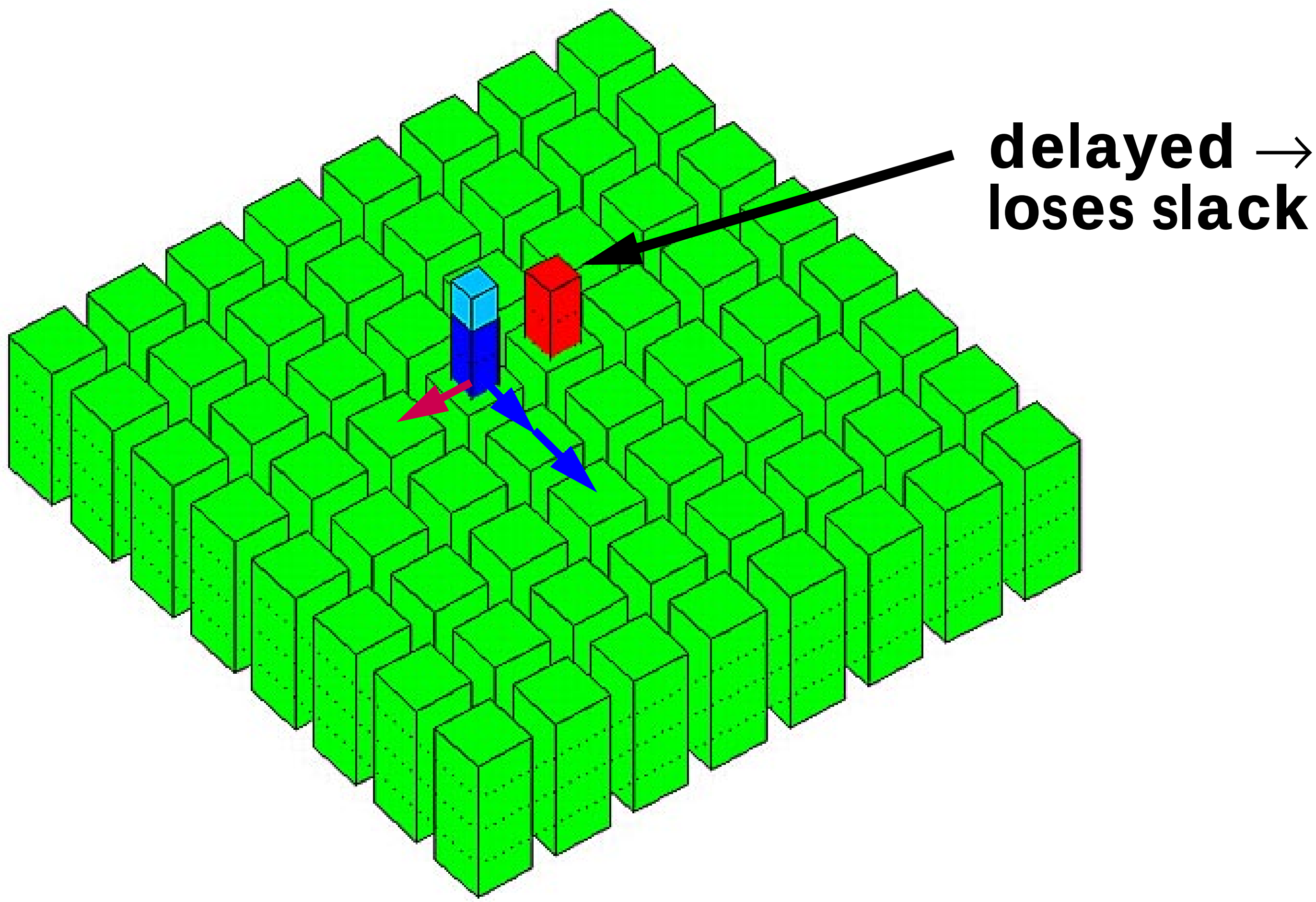

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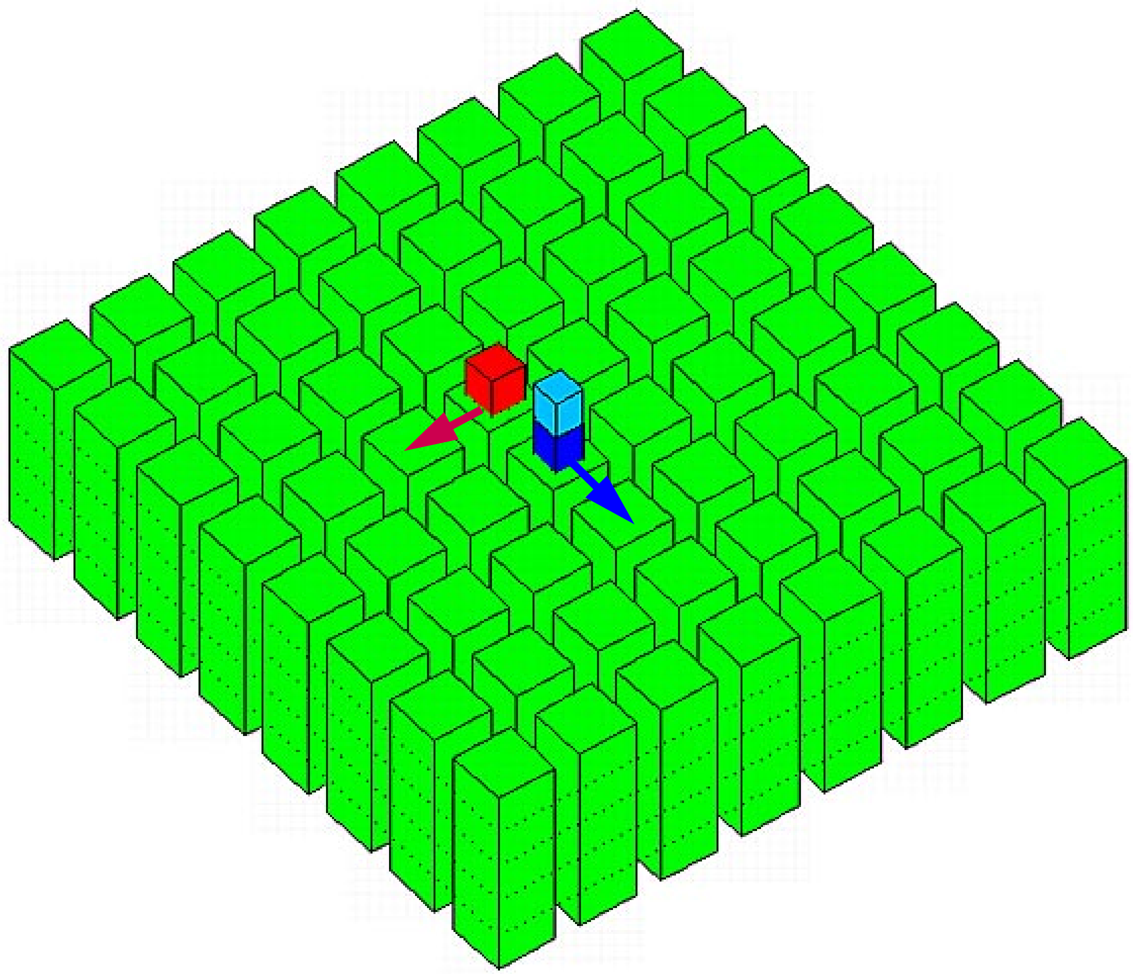

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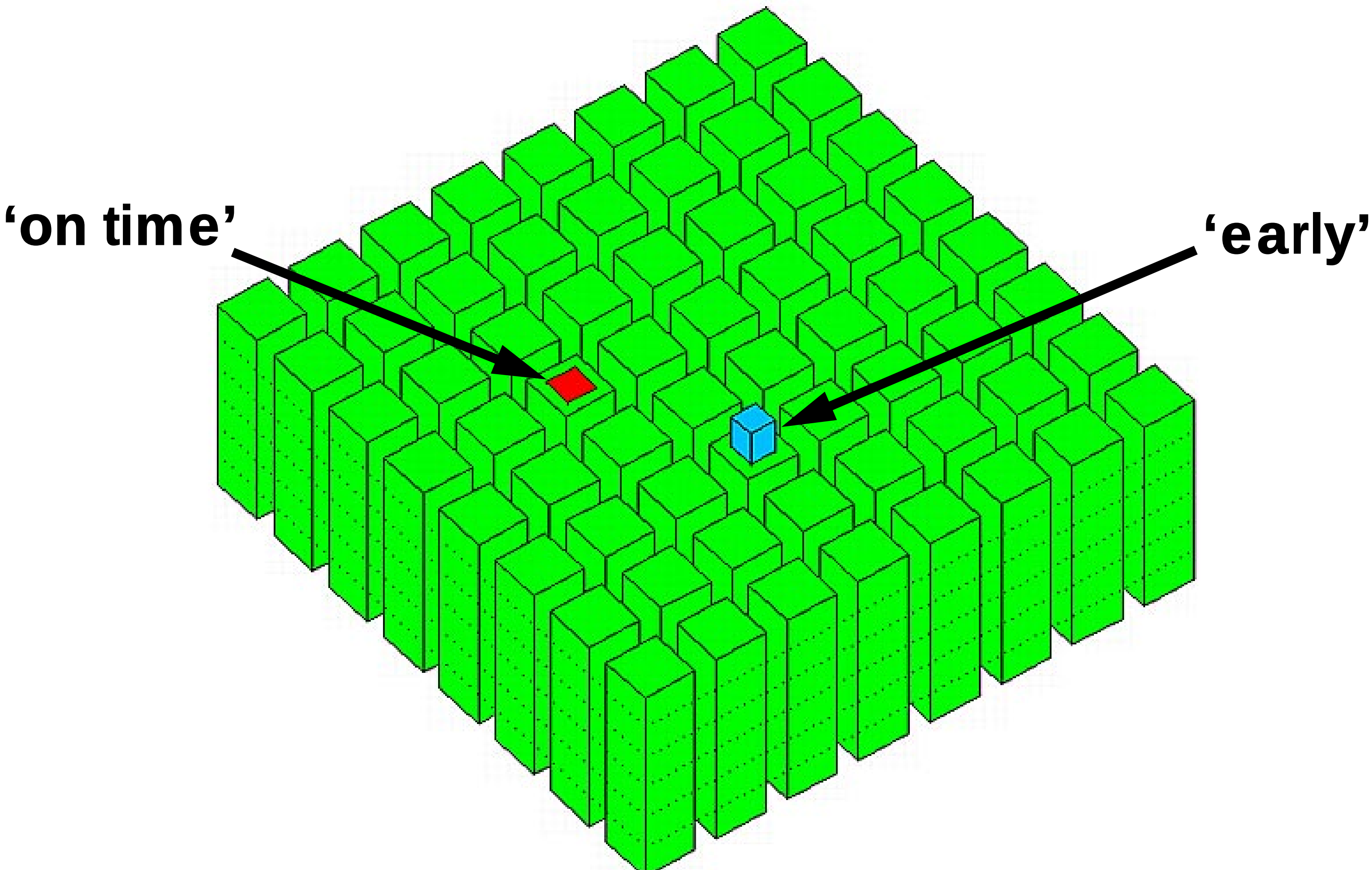


Avoids disruption in common cases

Implementation: Tokens

- Token passing implementation
  - Encode delta OTs and GTs implicitly
  - Extra bit per link
  - Small field per request
  - Simple algorithm in switches
- Advantages
  + Total order
  + Asynchronous
  + Variable link delay
- Disadvantages
  - Switch complexity

TOKENS ENCODE LOGICAL TIME

Timestamp Snooping Protocol

- Conventional MSI write-invalidate protocol
- Track if memory is owner
  - 1 state bit per block in memory (0.2% overhead)
  - Old idea from Synapse [Frank, 1984]
  - Avoids snoop responses
- Does not require synchronous broadcast

EXTENDS WELL-ACCEPTED SNOOPING PROTOCOLS

Outline

- Commercial Workloads
- Traditional Coherence
- Timestamp Snooping
- Evaluation
    - Workloads
    - Simulated System
    - Execution Time
    - Bandwidth
- Conclusion & Future Work

Workloads

- On-line transaction processing (OLTP)
  - IBM's DB2, TPC-C like, 400 MB in-memory DB
- Decision Support System (DSS)
  - IBM's DB2, Q12 from TPC-H, 100 MB in-memory DB
- Apache - web server
  - 8000 static files, 160 MB total
- Altavista - search engine
  - 500 MB index, 160,000 pages
- Barnes - scientific benchmark
  - 16K bodies

Simulated System

- Extended Virtutech's Simics full-system simulator
- 16 processors
- SPARC/Solaris 7
- Processor can execute 4 billion instructions/second including L1 cache misses
- Parameters
  - 4 MB, 4-way set-associative blocking L2 caches
  - 64 Byte blocks
- Vary protocol
  - Timestamp Snooping
  - DirOpt: non-blocking directory protocol
- Interconnect
  - 2D Torus (4x4)
  - Interconnect bandwidth unconstrained

Latency Assumptions

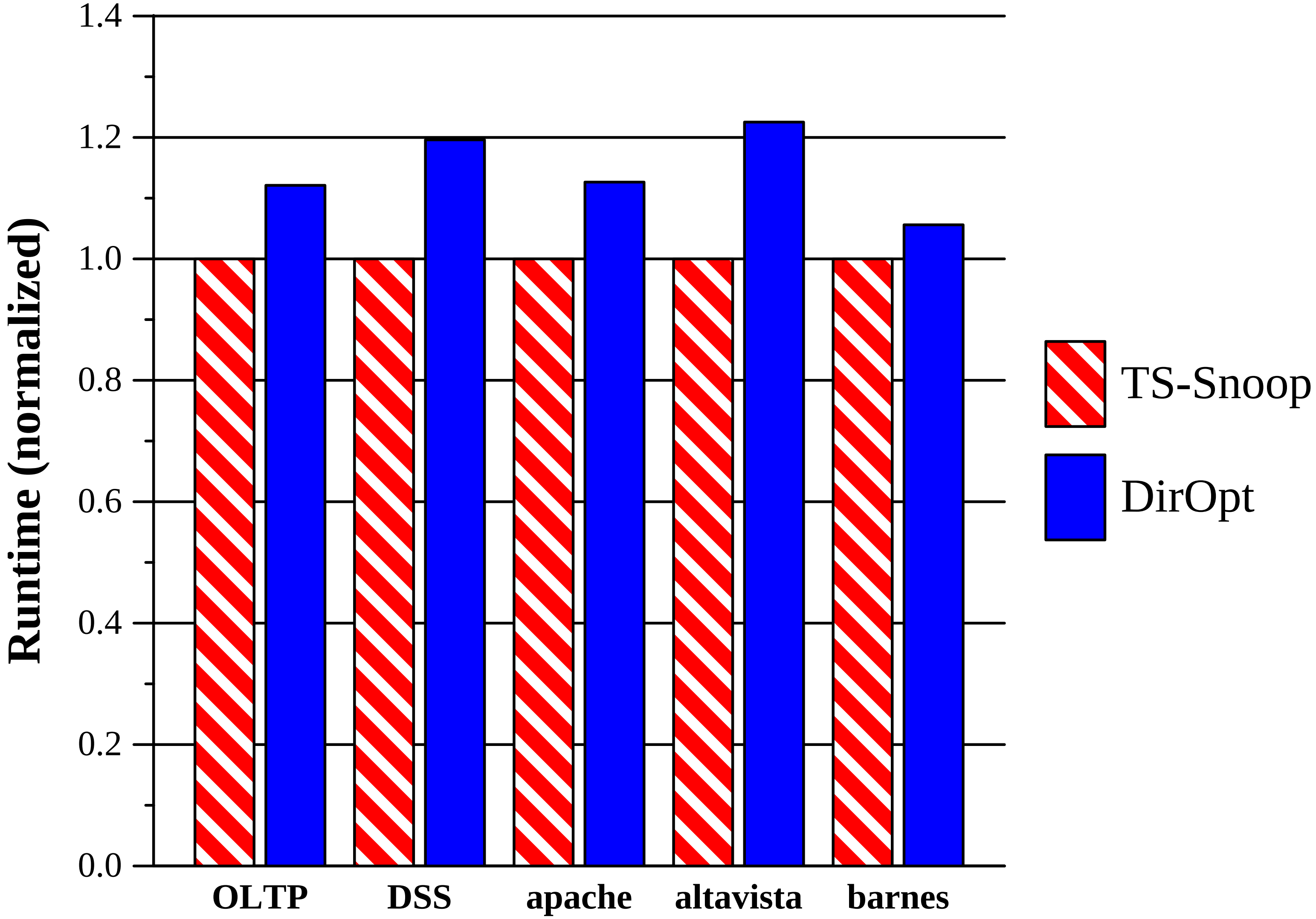
- Switch-to-switch - 15 ns
- Enter & exit network - 4 ns
- DRAM/directory access - 80 ns
- Cache SRAM access - 25 ns

	from Memory	from Cache
Directory (CC-NUMA)	2 hop + DRAM 148 ns	3 hop + directory + SRAM 207 ns
TS Snoop	2 hop + DRAM 148 ns	2 hop + SRAM 93 ns

same

2x

Execution Time Results



TIMESTAMP SNOOPING IS 6-23% FASTER THAN DIRECTORIES

Bandwidth Assumptions

- Back-of-the-envelope calculation
  - Data at memory
  - One request, one data response
  - Dependent on number of processors

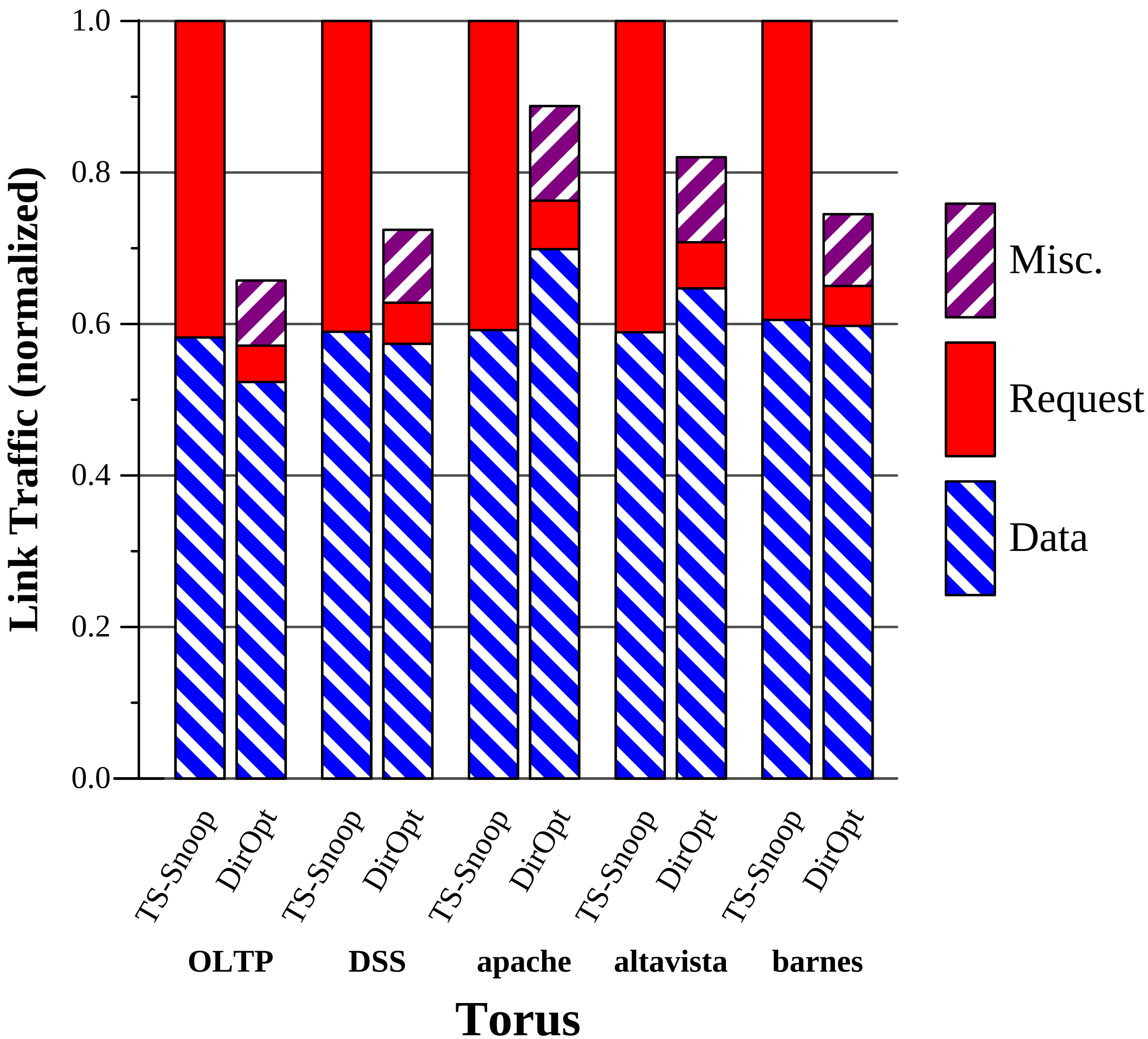
	Request	Data Response	Total
Message Size	8 Bytes	72 Bytes	
Directory (CC-NUMA)	Unicast 2 × 8 B	Unicast 2 × 72 B	= 160 B
TS Snoop	Broadcast 15 × 8 B	Unicast 2 × 72 B	= 264 B

8x

same

CONSERVATIVE ESTIMATE: DIRECTORIES 53% LESS BANDWIDTH/MISS

Bandwidth Results



DIRECTORIES USE 17-37% LESS BANDWIDTH

Conclusion

- **Comparison vs directory protocols**
  - **Efficient cache-to-cache transfers $\rightarrow$ performance advantage**
  - **Latency/bandwidth trade-off**

- **Comparison vs current SMPs**
  - **More interconnect choices**
  - **Less global communication**

- **Future work**
  - **Multicast snooping on Timestamp Snooping network**
  - **Bandwidth adaptive snooping hybrid**

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