Data-Centric Execution of Speculative Parallel Programs

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MICRO 2016

Executive summary

Many-cores must exploit cache locality to scale

Current speculative systems, e.g. TLS or TM, **do not exploit locality**

Spatial Hints: run tasks likely to access the same data in the same place

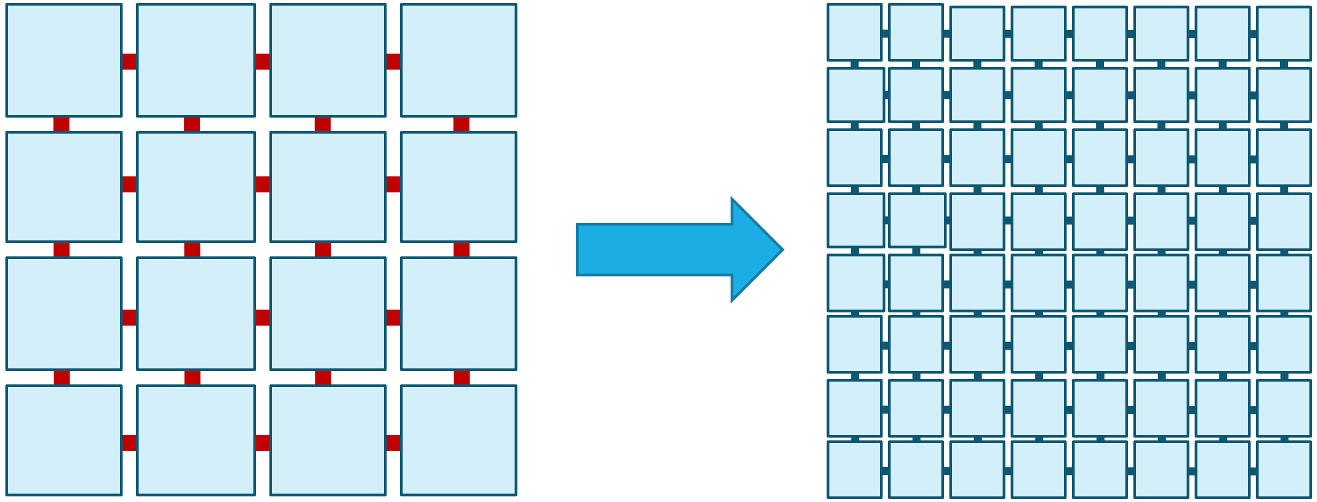
- A software-given **hint** denotes the data a new task is likely to access
- Hardware maps tasks with the same hint to the same place
- Hardware uses hints to perform locality-aware load balancing

Our techniques make **speculative parallelism practical** at large scale

- It is easy to modify programs to convey locality through hints
- Performance improves by 3.3x at 256 cores
- We reduce network traffic by 6.4x and wasted work by 3.5x

Prior speculative systems scale poorly

TRANSACTIONAL MEMORY (TM) SCHEDULERS	SPATIAL HINTS
Reduce wasted work of coarse-grain txns	**Make accesses local** for fine-grain tasks
Limit concurrency: **When** to run a task?	Less data movement: **Where** to run a task?



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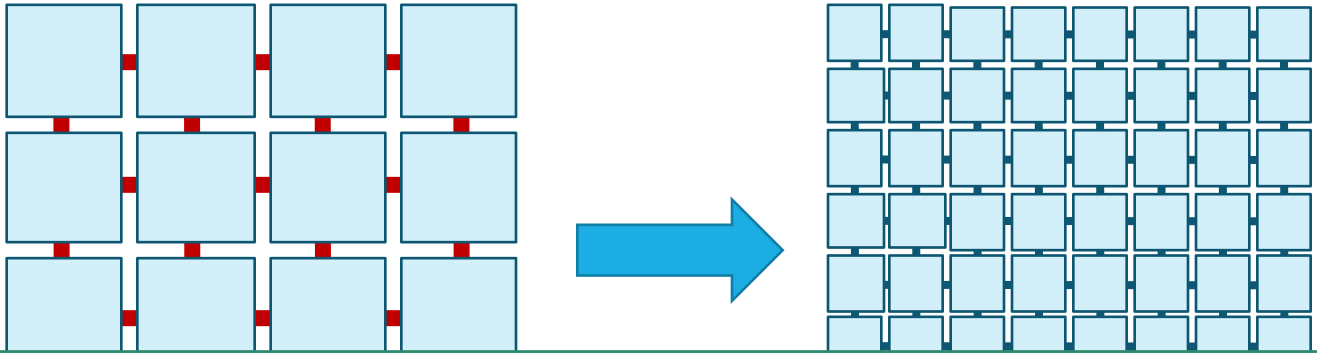


Spatially map tasks for improved locality and less waste

Prior non-speculative locality techniques do not work for speculation

STATIC TASK MAPPING

Data dependences known a priori

- Linear algebra, Anton 2 [ASPLOS '13]

Graph partitioning

- **Localizes** communication and scheduling
- **Slow preprocessing** step
- **Cannot adapt** to imbalance

DYNAMIC TASK MAPPING

Work stealing

- **Cheap, local** enqueues
- Steals to **adapt** to imbalance
- **Limited** application types
- Stealing **interferes** with speculation

Baseline Architecture: Swarm [MICRO '15]

Baseline Swarm execution model

Programs consist of timestamped tasks

- Tasks can create children tasks with >= timestamp
- Tasks appear to execute in timestamp order

```
swarm::enqueue(function_pointer,
               timestamp,
               arguments...);
```

General execution model supports ordered and unordered parallelism

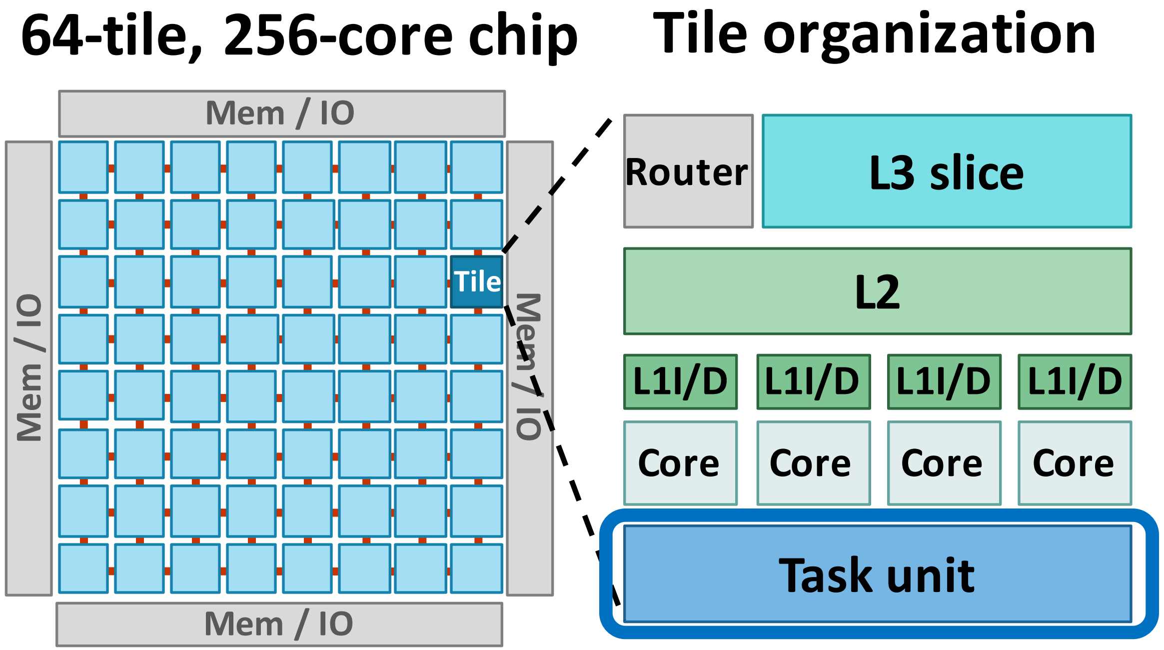
Baseline Swarm architecture

Speculatively executes tasks out of order

Large hardware task queues

Scalable ordered speculation

Scalable ordered commits

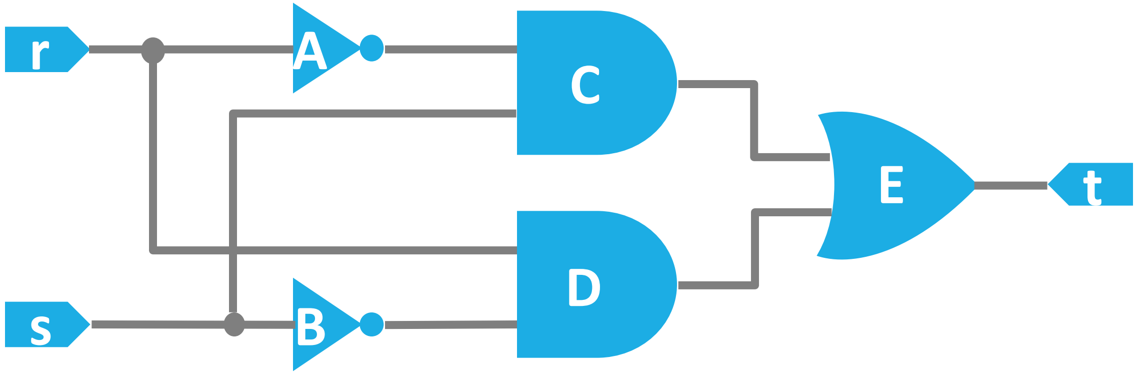


Efficiently supports tiny speculative tasks

Spatial Hints in Action

COMBINING SPECULATION AND LOCALITY

Example: Discrete event simulation (DES)



r	s	t = r XOR s

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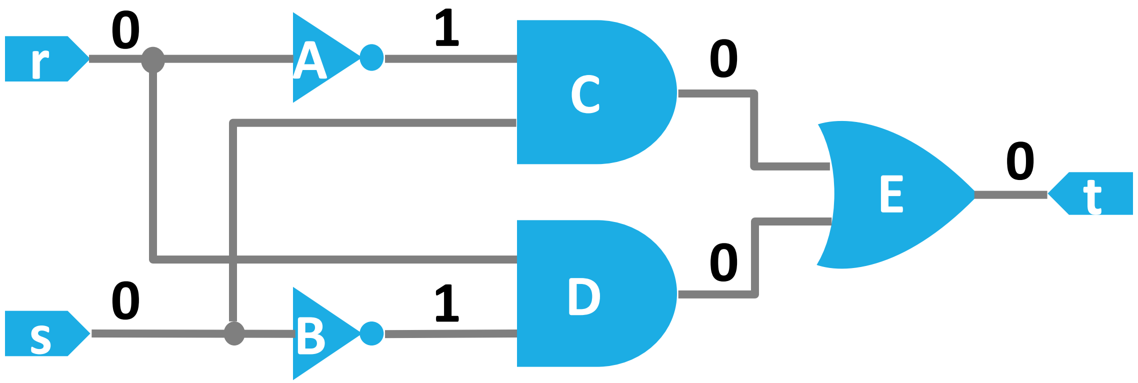

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0	0	0

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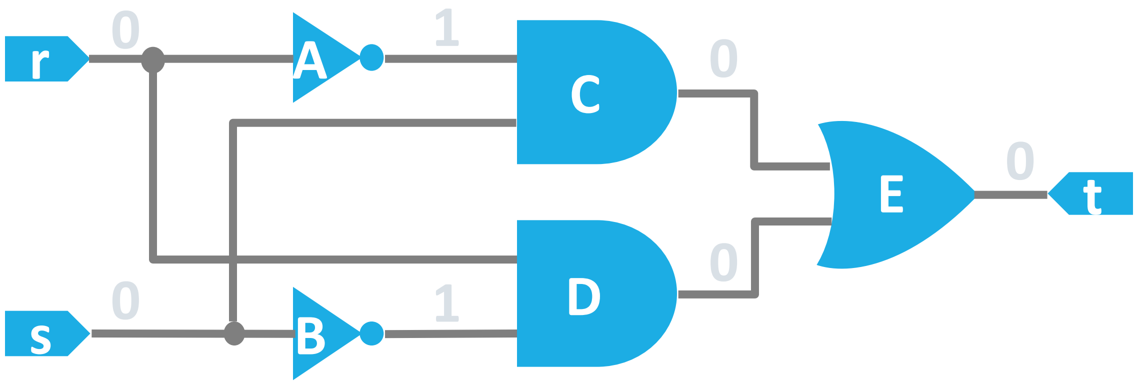

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Tasks

Order = Simulated time (*ns*)

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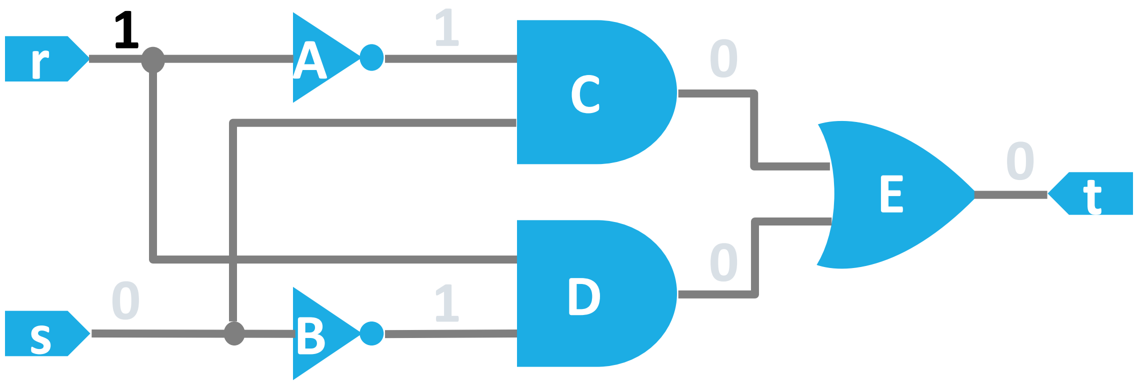

r	s	t = r XOR s
0	0	0
1	0	

Tasks

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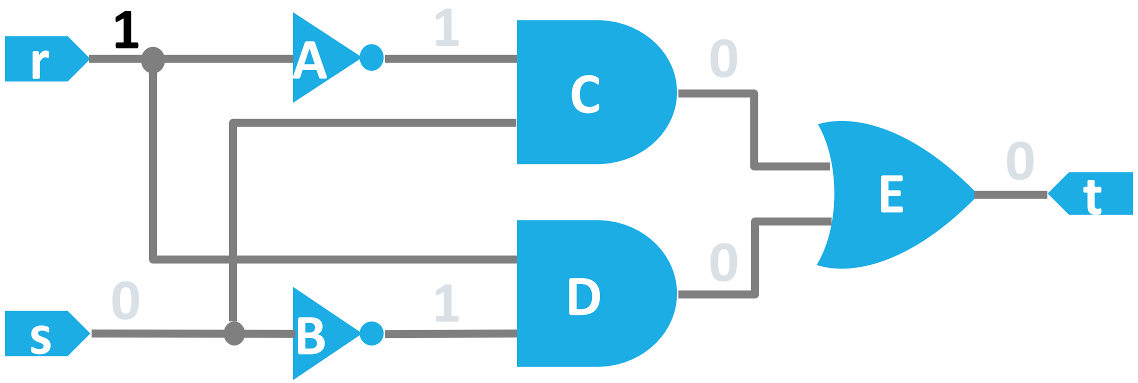

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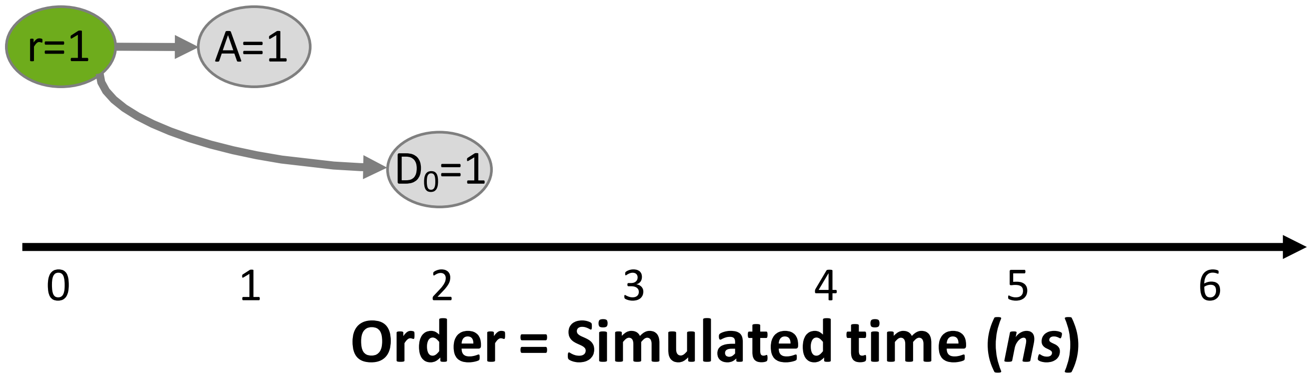

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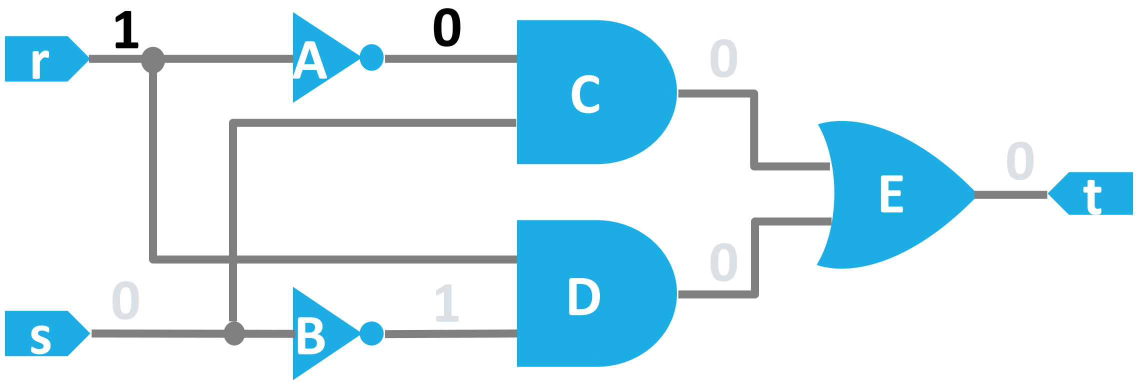

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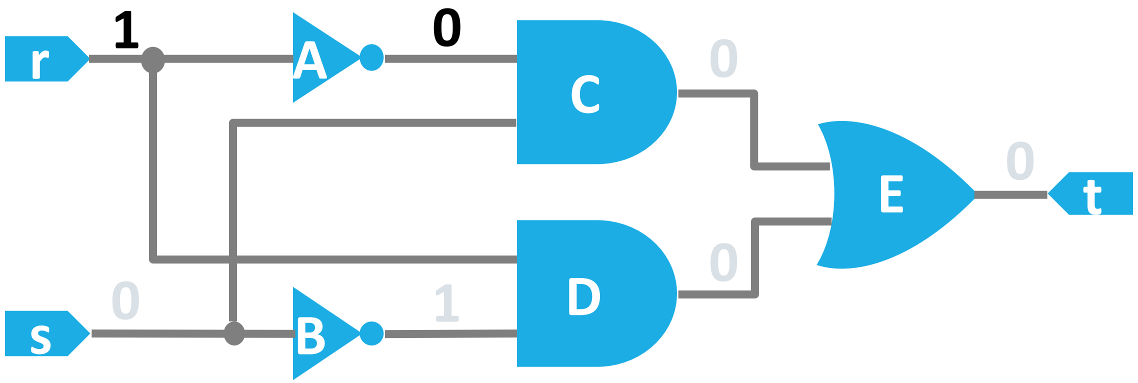

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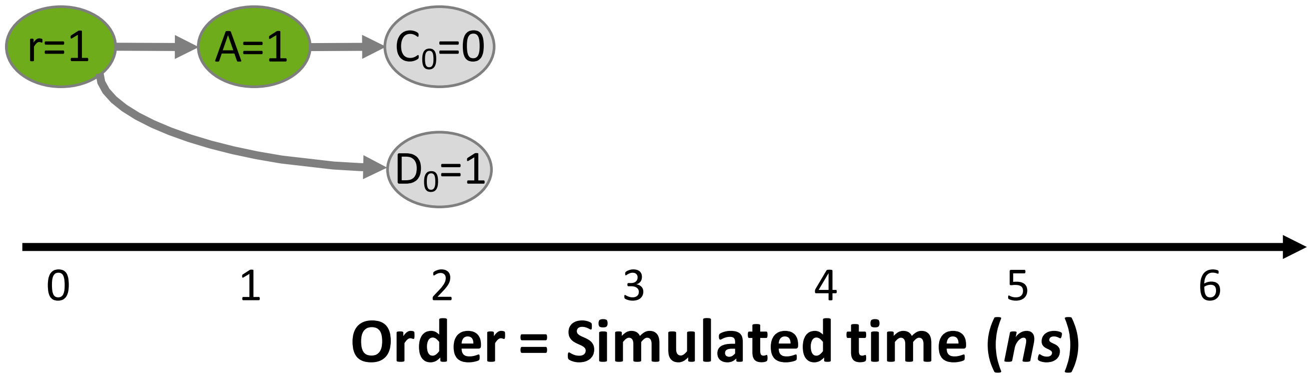

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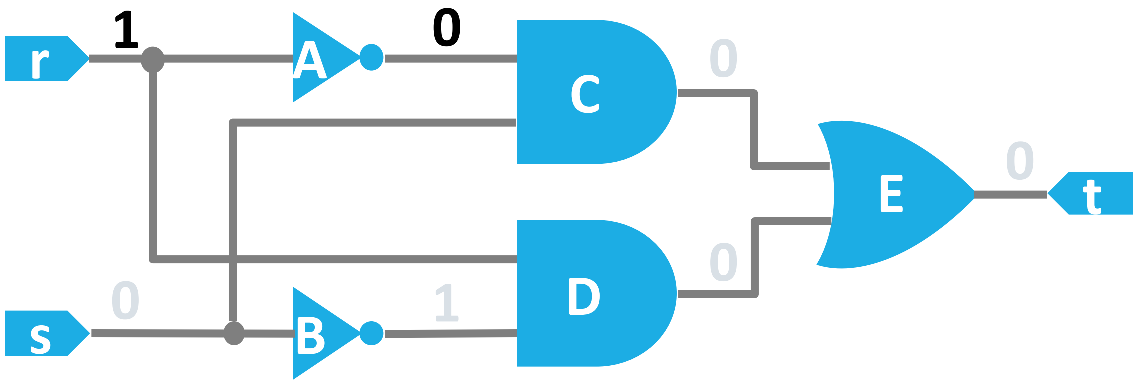

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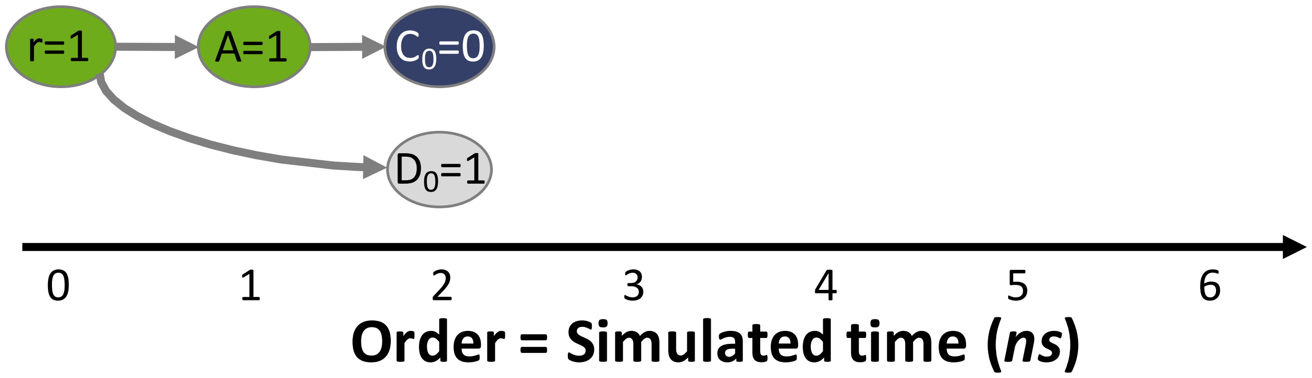

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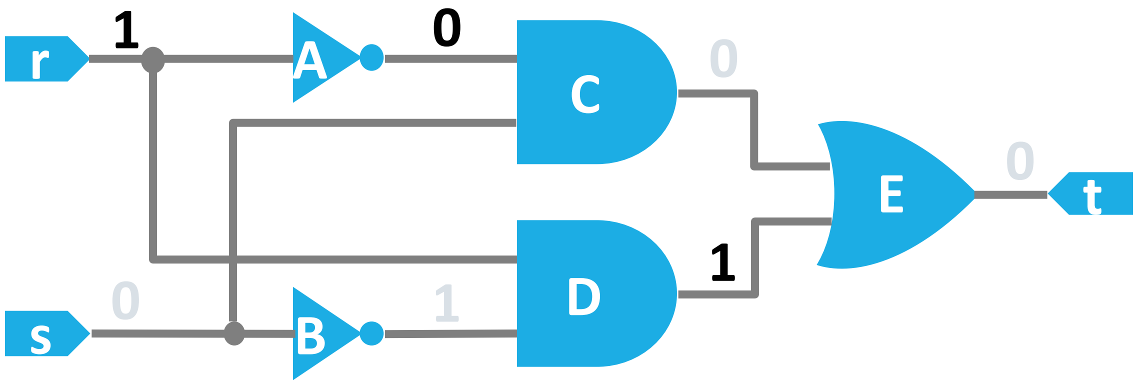

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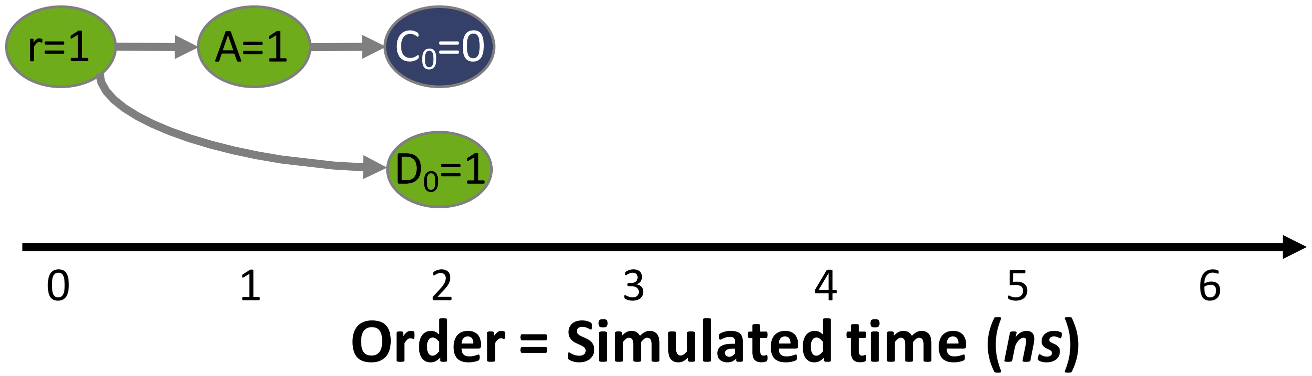

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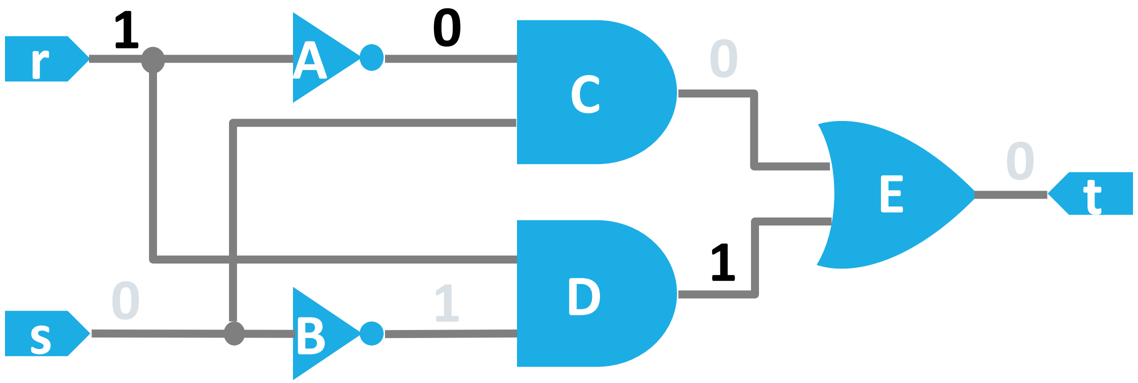

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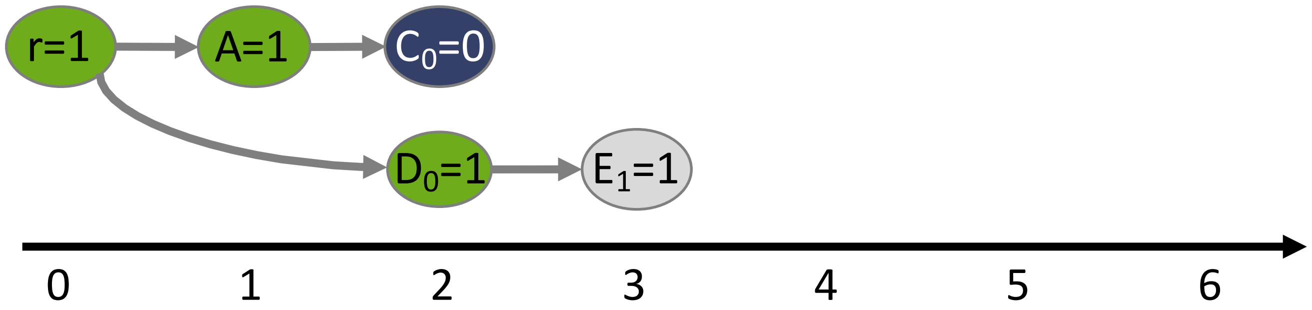

Order = Simulated time (*ns*)

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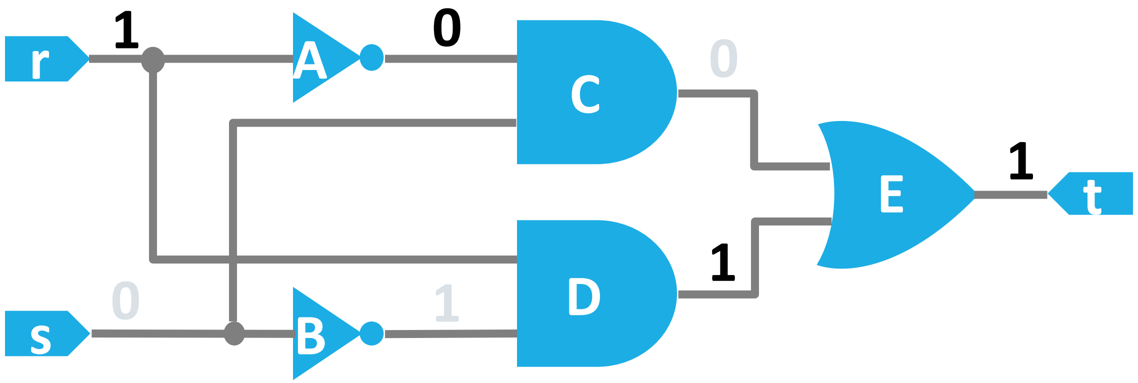

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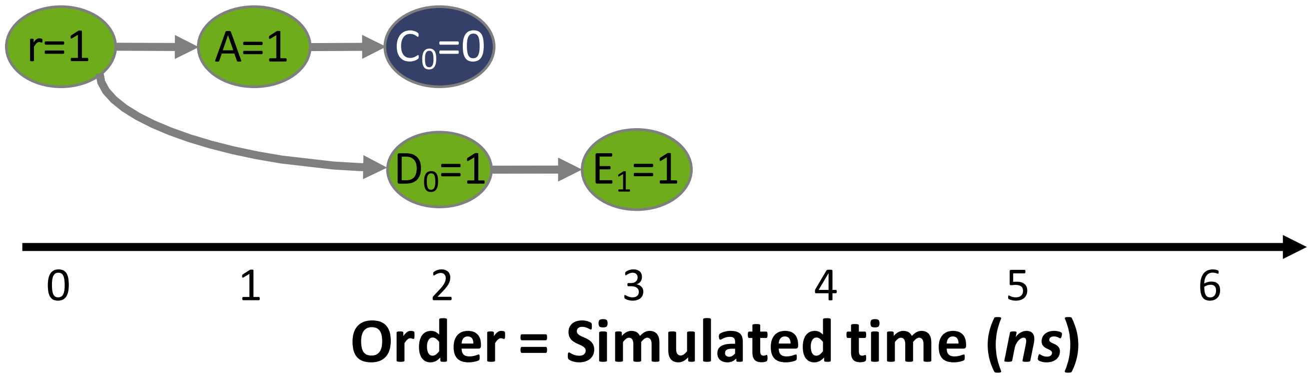
Tasks



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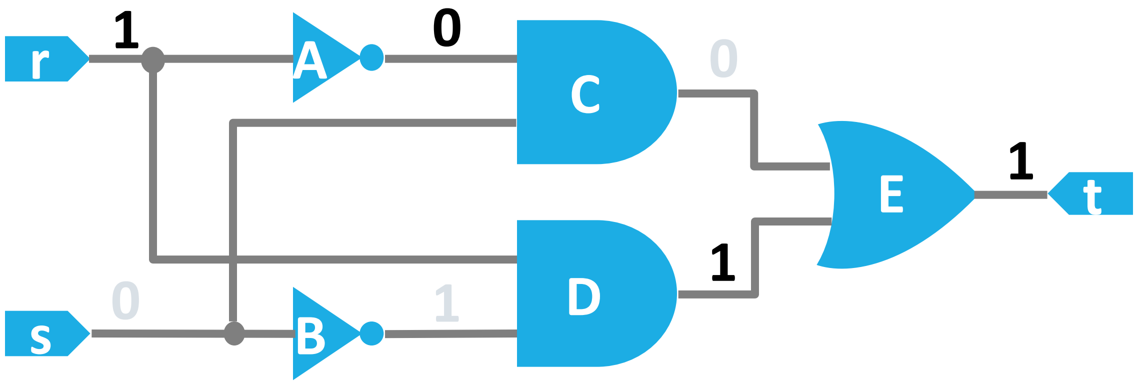

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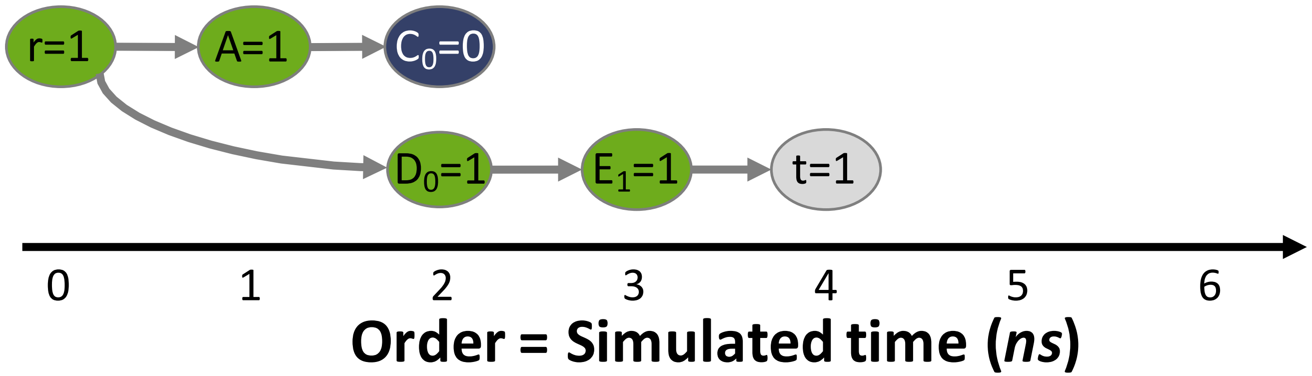

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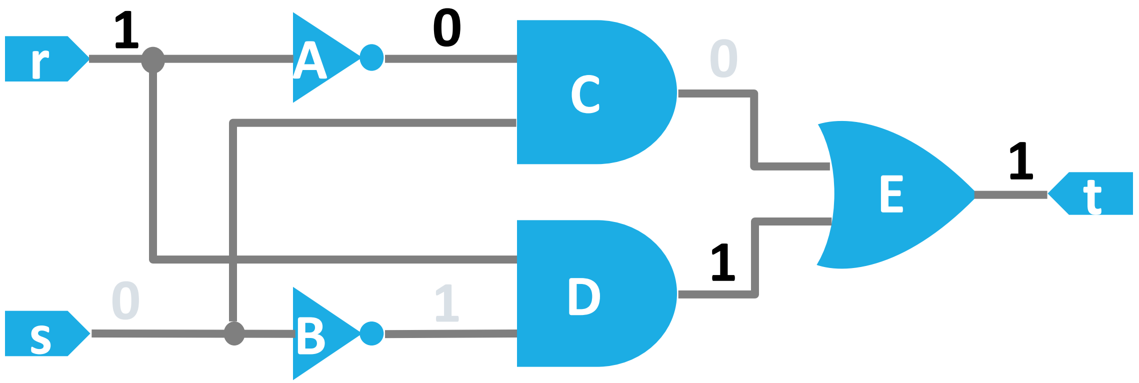

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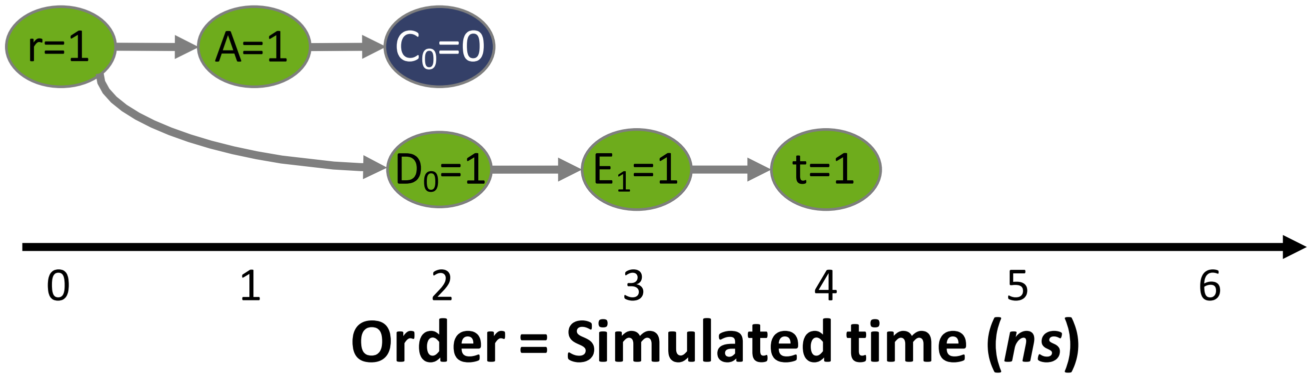

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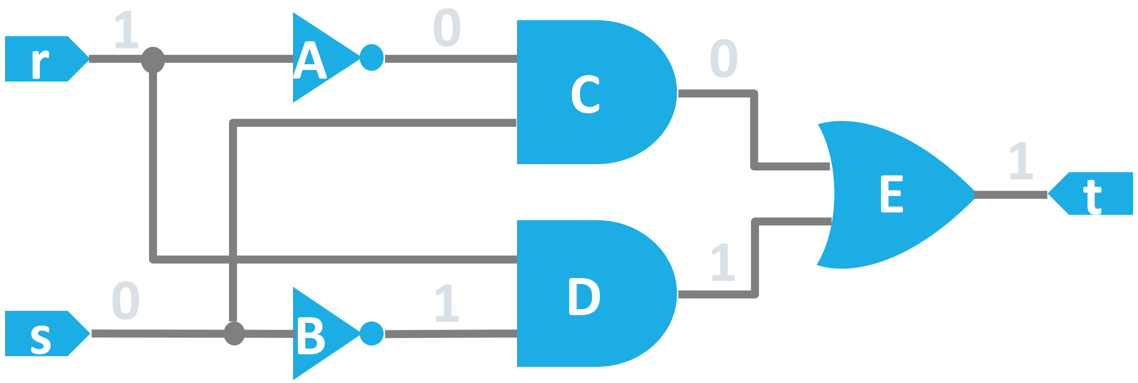

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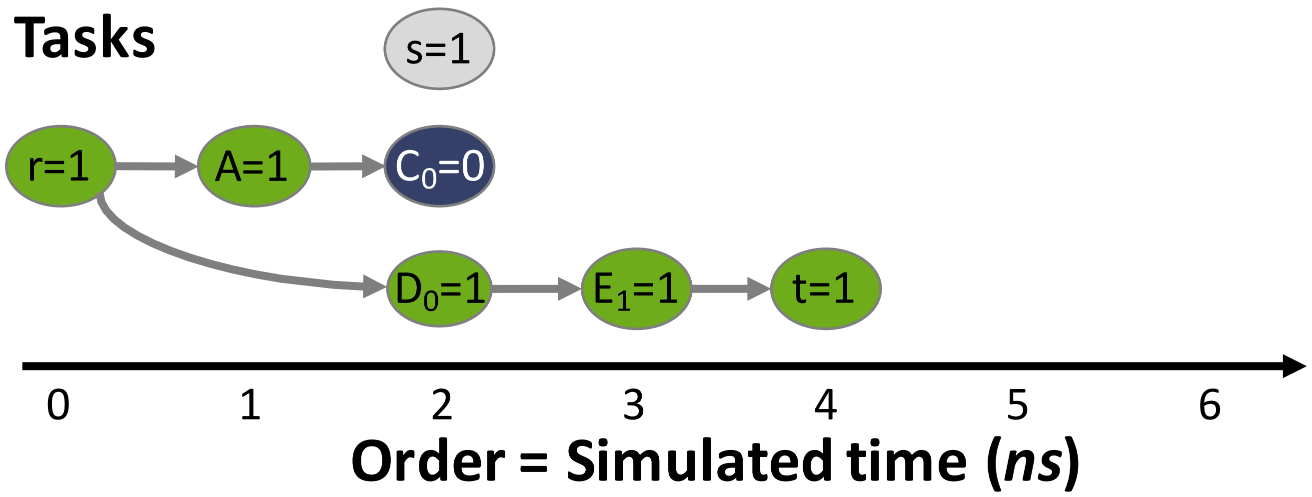

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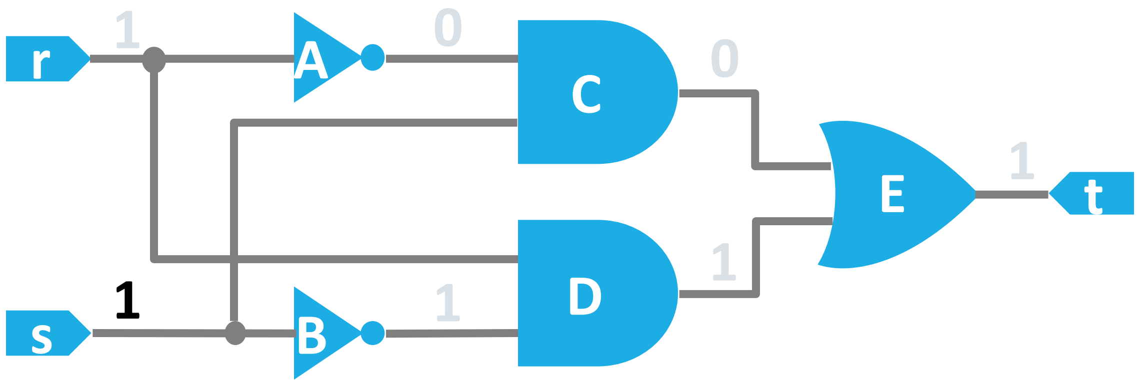

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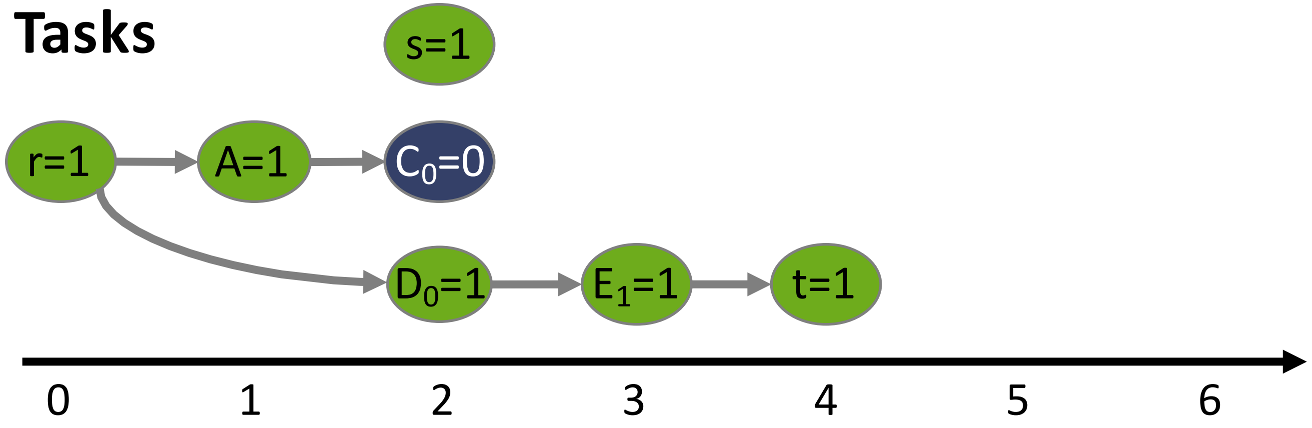

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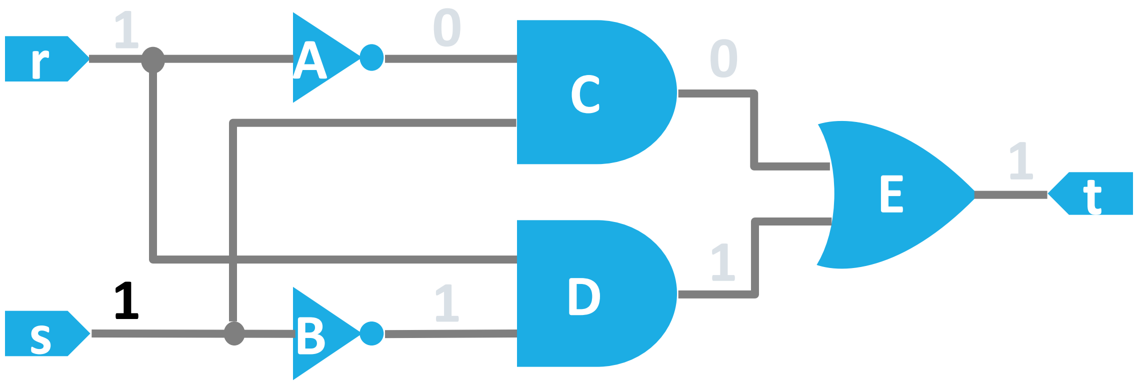

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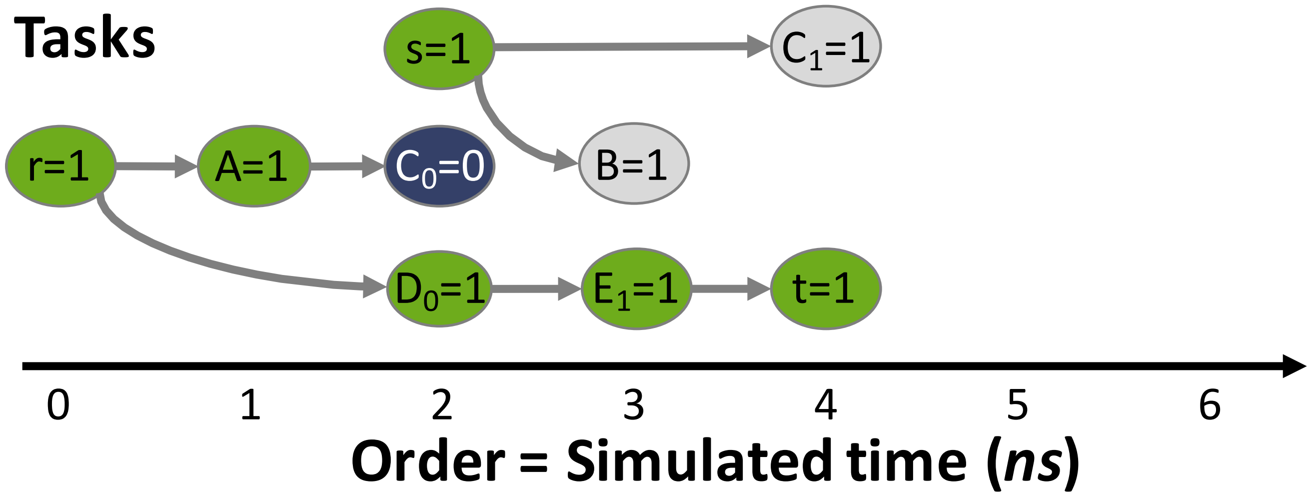

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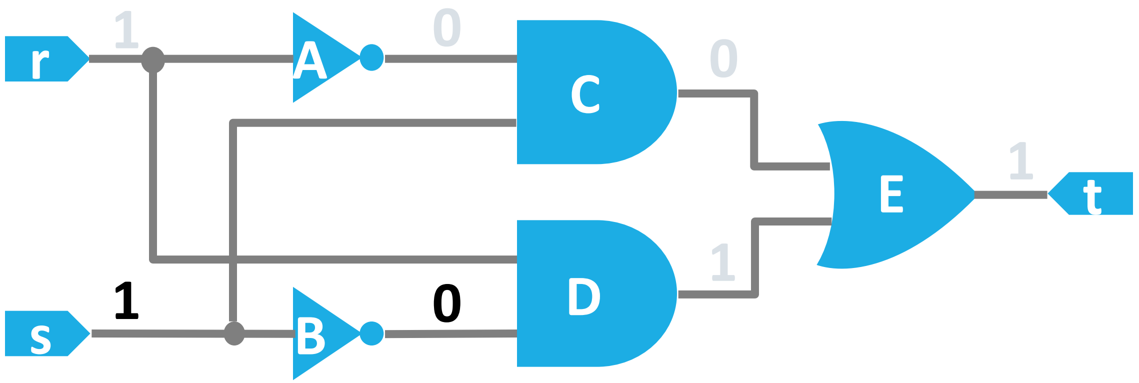

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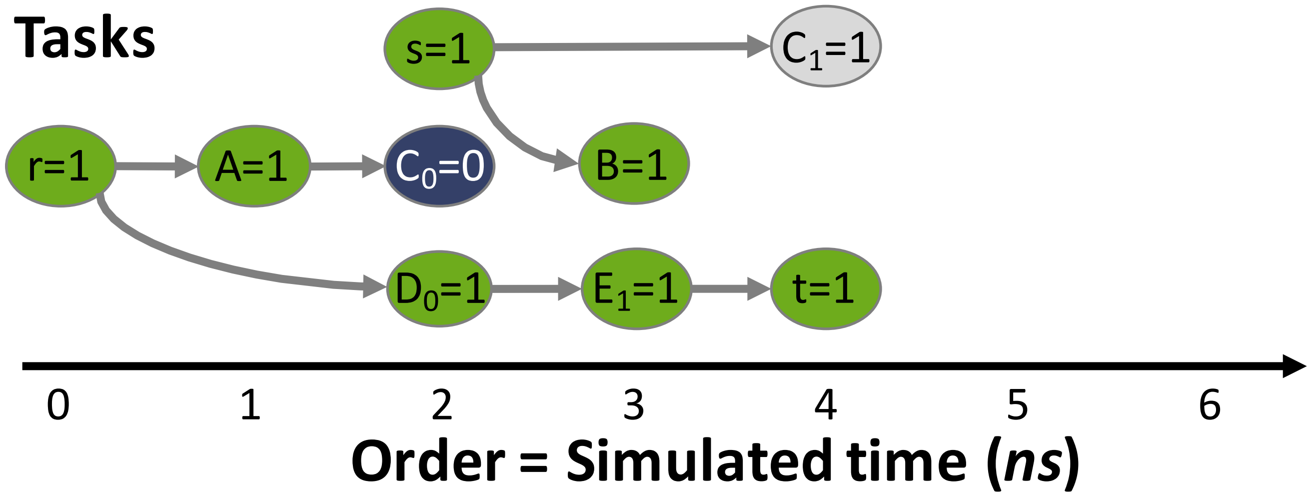

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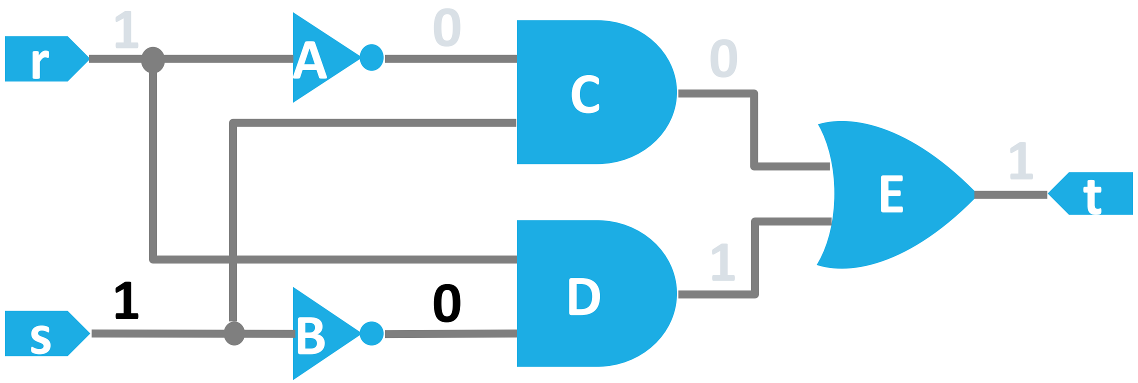

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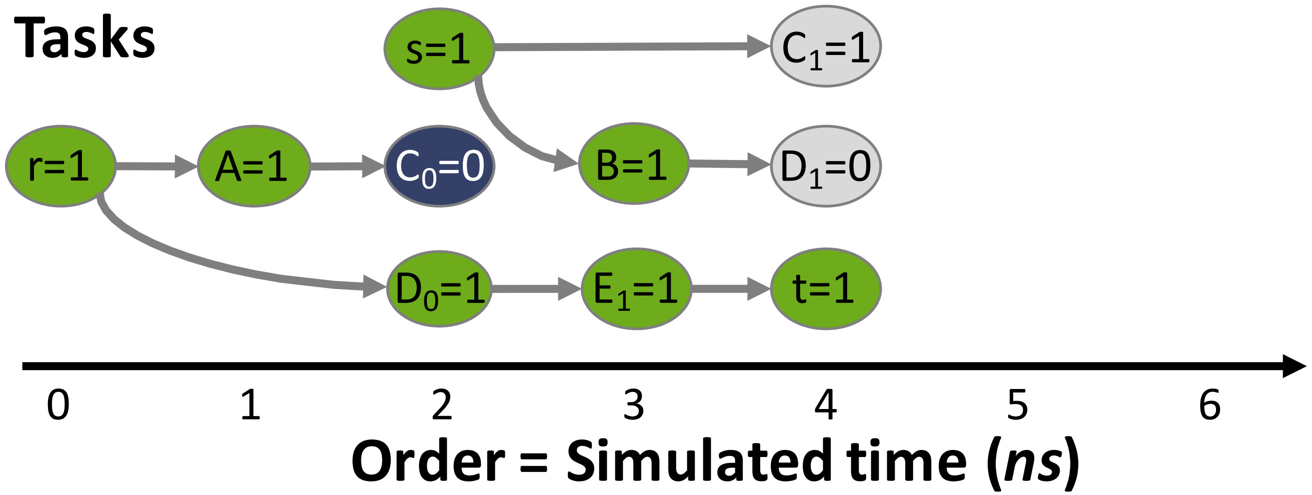

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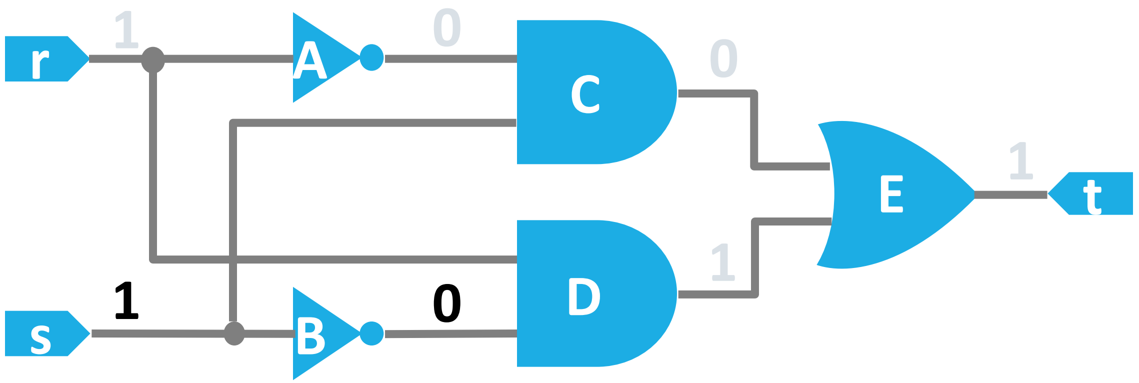

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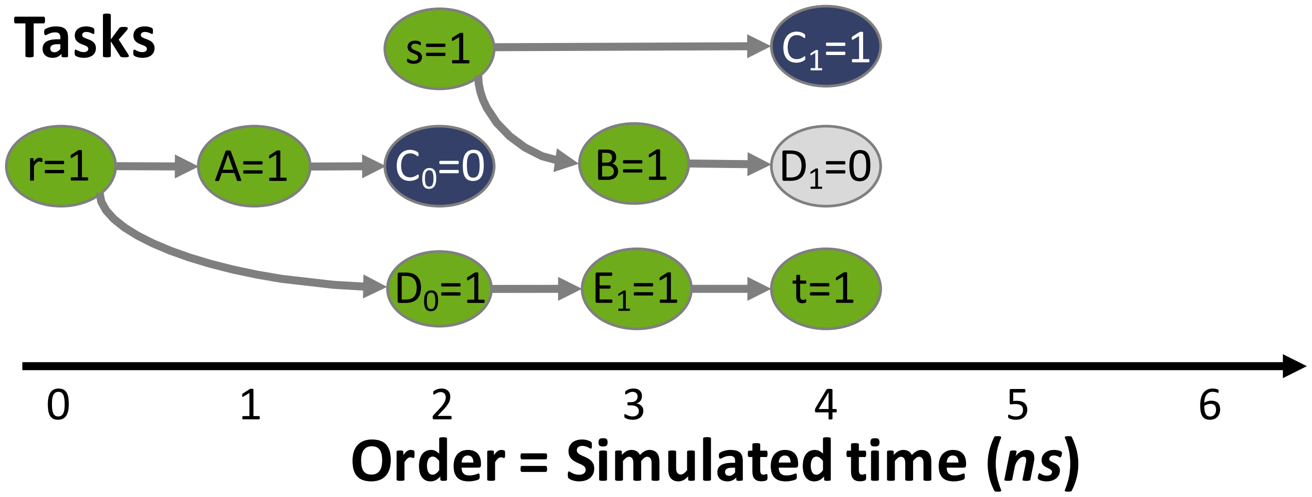

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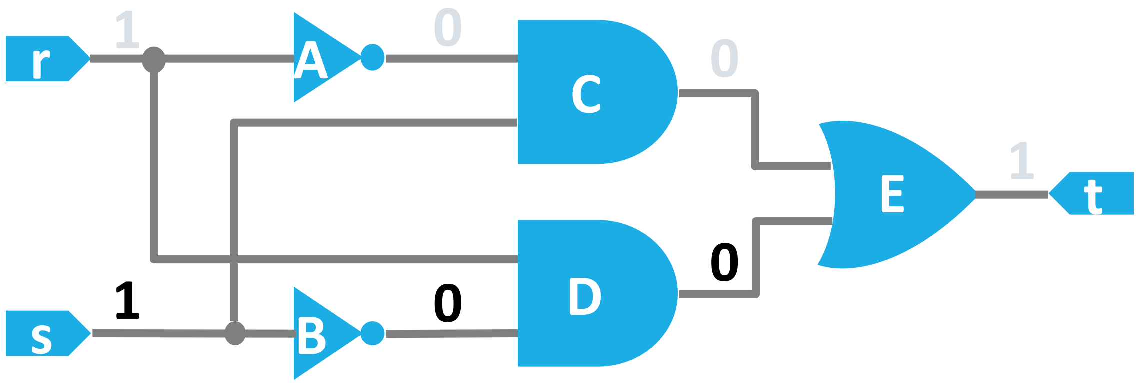

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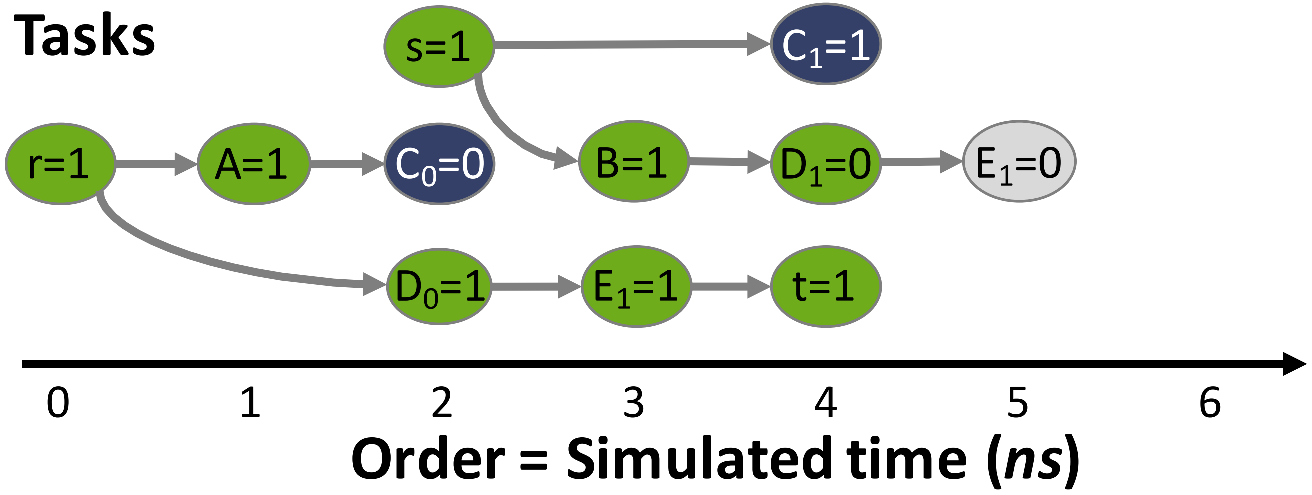

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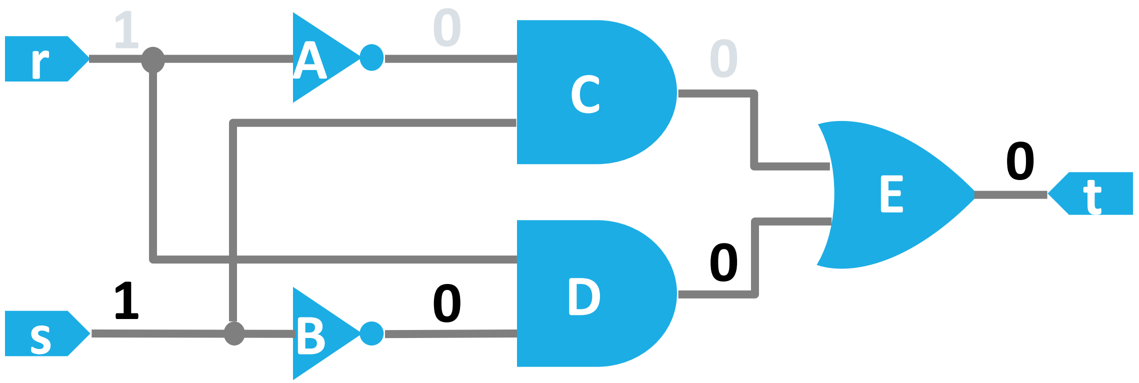

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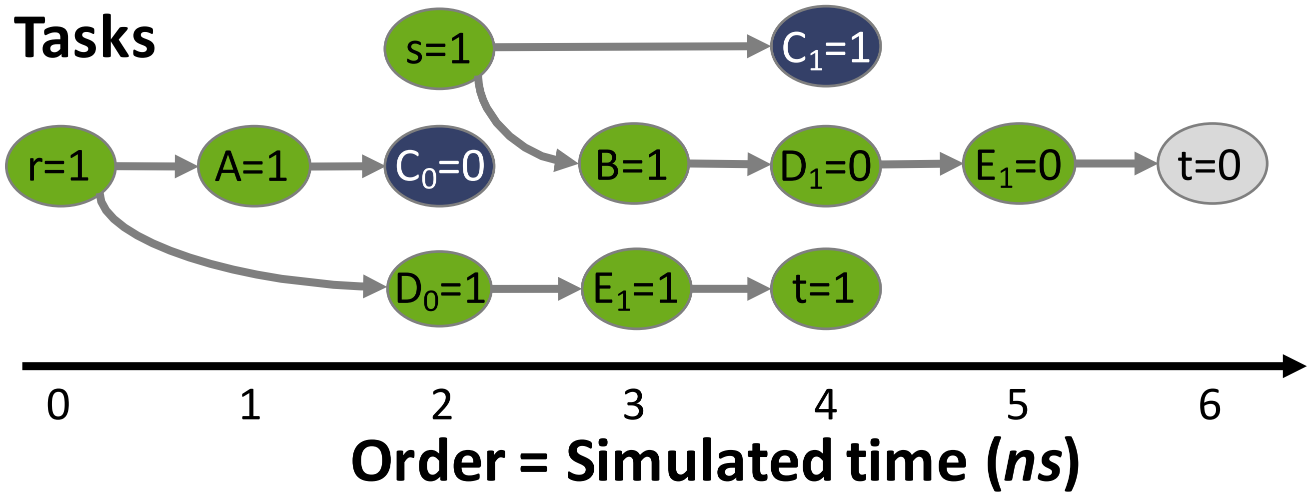

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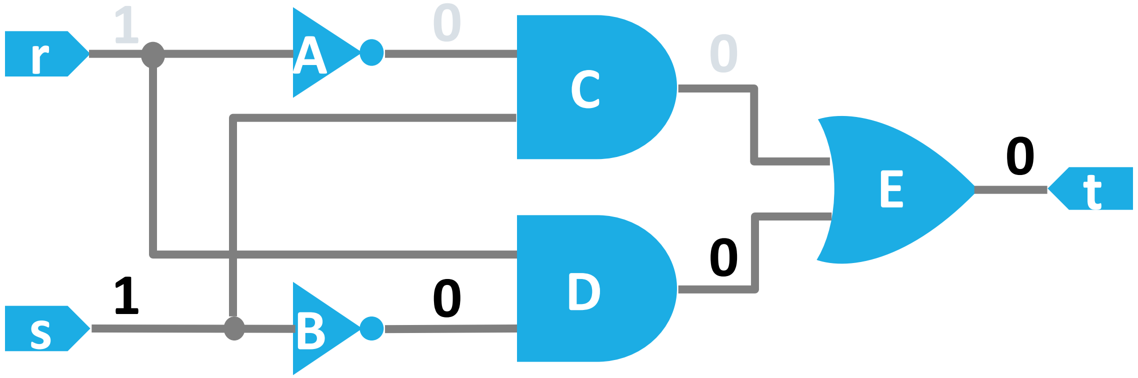

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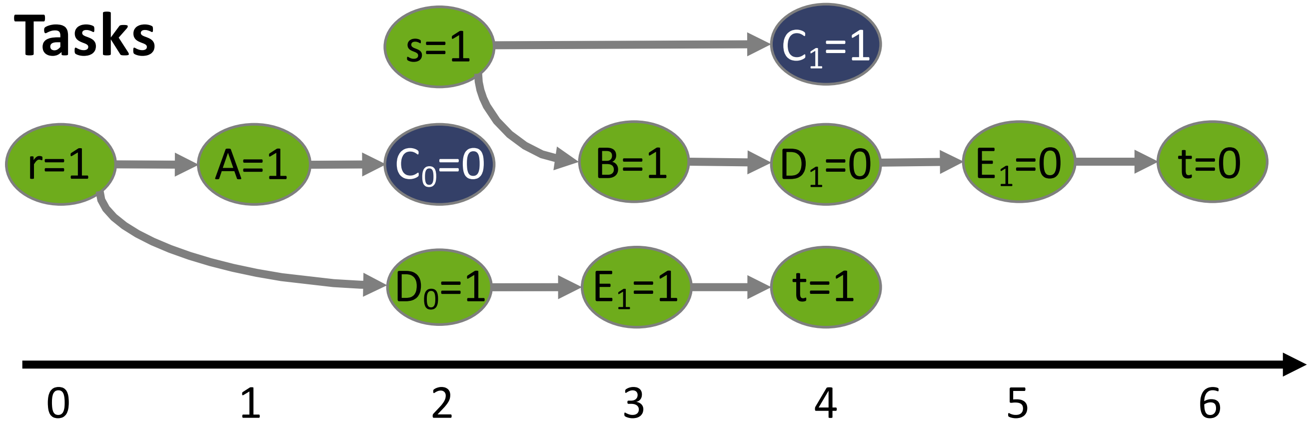
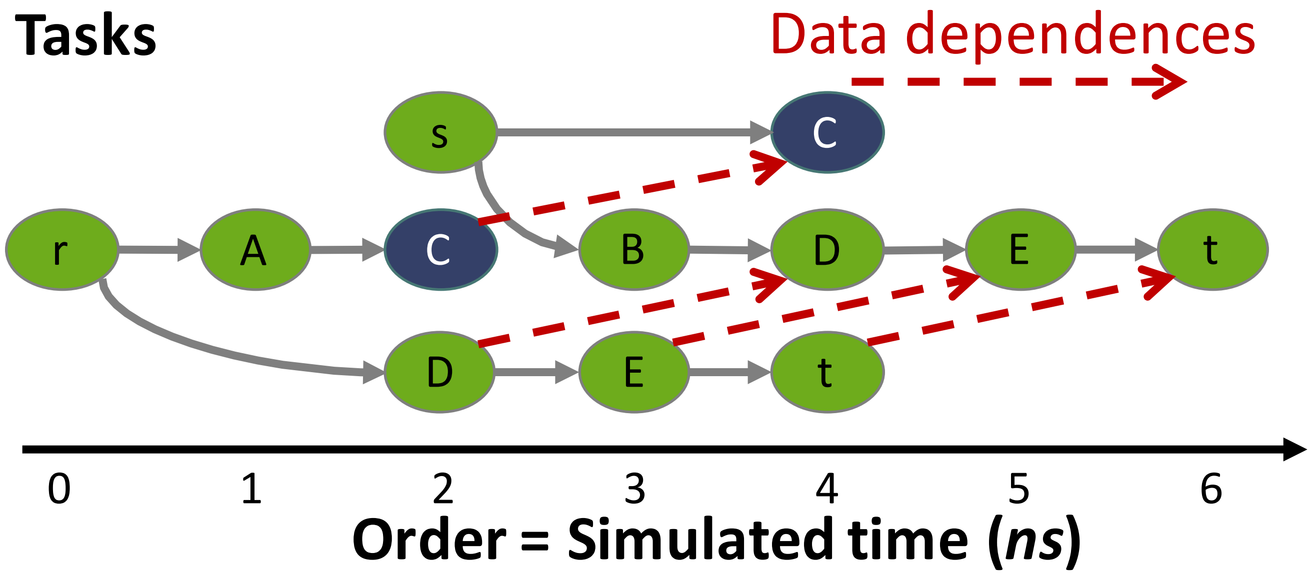
Tasks

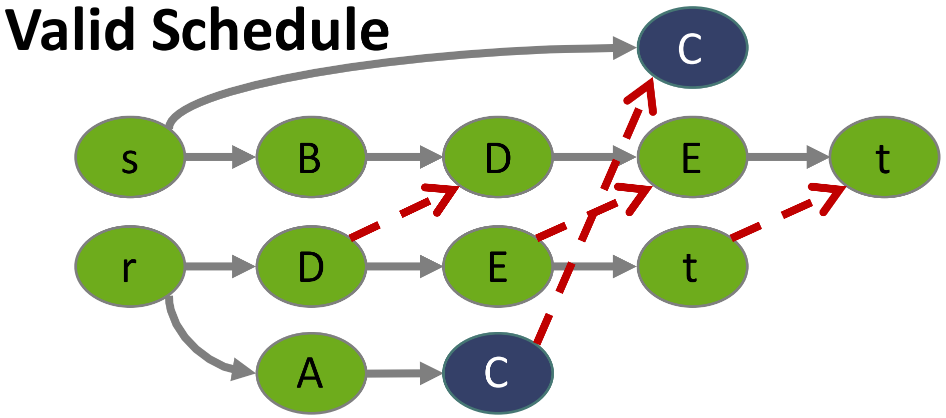


Order = Simulated time (*ns*)

Extracting parallelism in DES

Execute independent tasks out of order





2.4x parallelism
(more in larger circuits)

Parallelism is plentiful despite data dependences

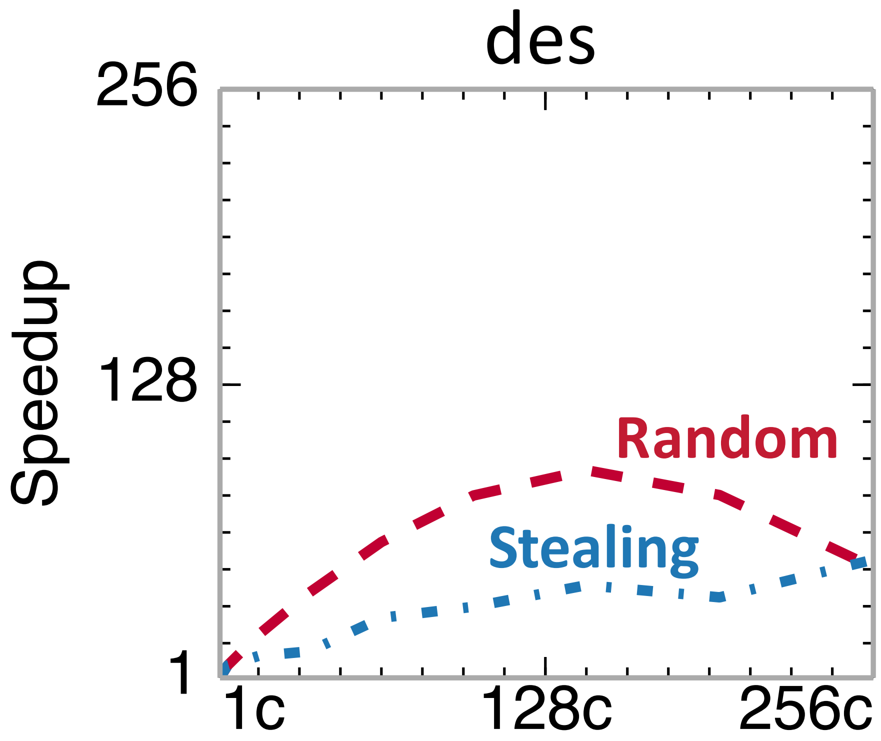
Speculation scales poorly without locality

Swarm sends new tasks to **random** tiles

- Good for **load balance**
- **Poor locality** hurts scalability beyond 100 cores

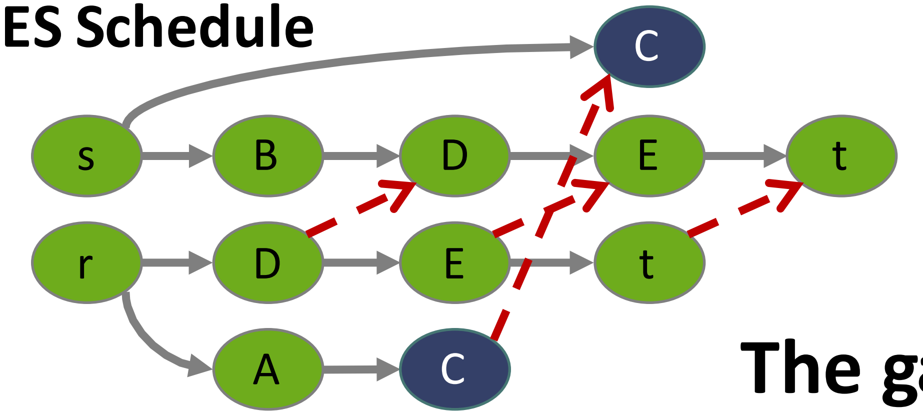
Work stealing: a non-speculative scheduler

- Enqueue new tasks locally
- Steal from the most-loaded tile
- Not a good strategy for DES



Where is the locality?

DES Schedule



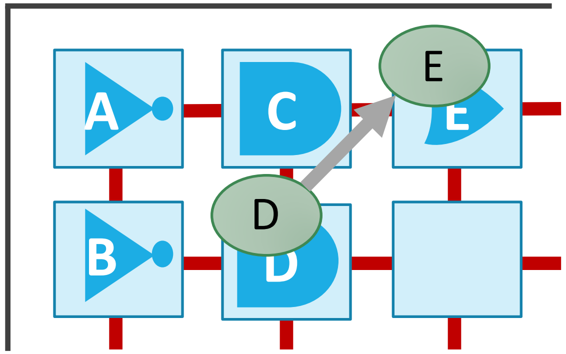
Each task operates on a single gate

The gate is known when the task is created

With fine-grain tasks, most data accessed is known at creation time

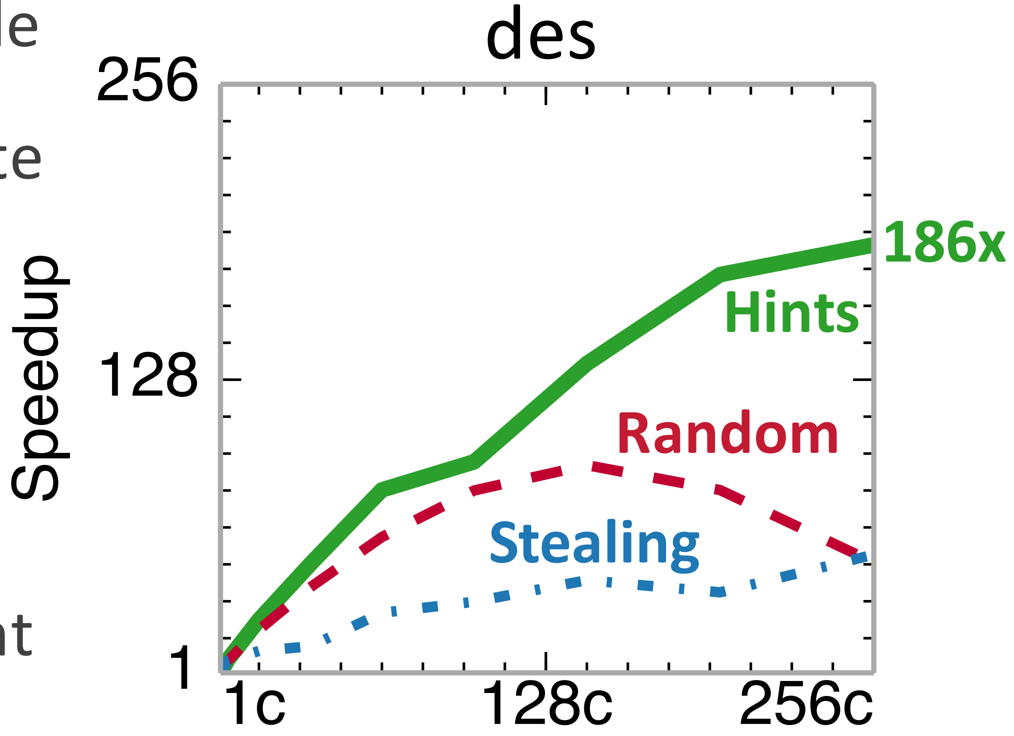
Data-centric speculation scales well

Hints: map each gate to a statically-chosen tile



Send new tasks for a gate to its corresponding tile

1. Less data movement
2. Conflicts are local, cheap, and less frequent



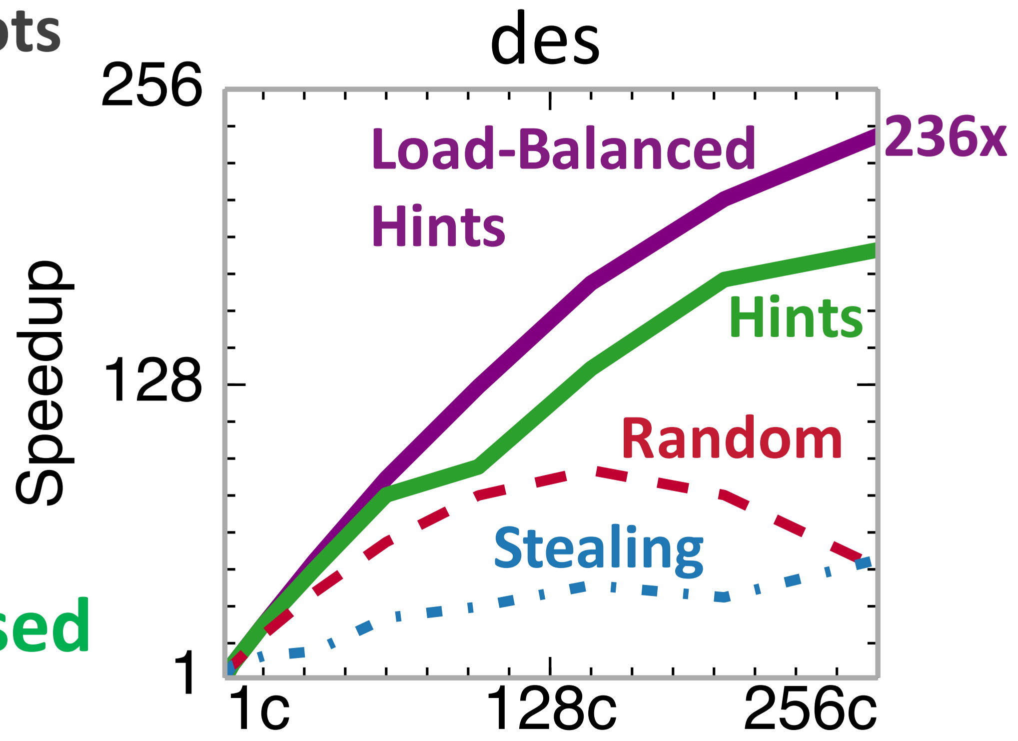
But we can do better!

Load-balanced speculation scales best

Static gate-to-tile mapping may cause **hotspots**

- E.g. some gates toggle more frequently

Dynamically remap gates (**Hints**) across tiles



Programmer knows *most* of the data accessed

Spatial Hints convey program-level knowledge to exploit locality

Spatial Hints Implementation

Hint mechanisms are straightforward

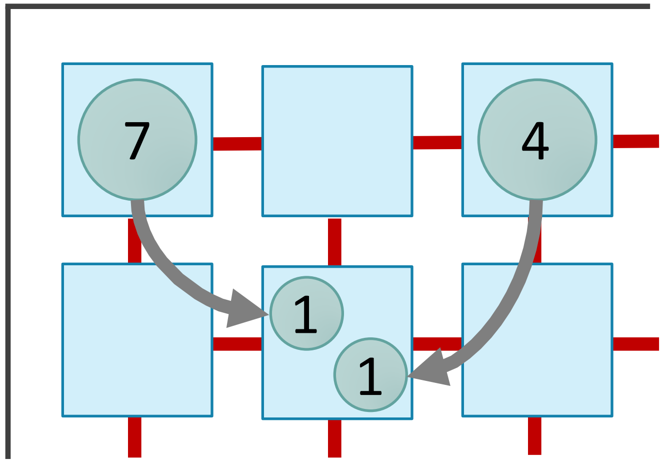
SOFTWARE

A **Spatial Hint** is an integer value
- Given at task creation time
- Denotes data likely to be accessed by the task
- E.g. the gate ID in DES

HARDWARE

Hashes each new task's **Hint** to a tile ID

Serializes same-**Hint** tasks

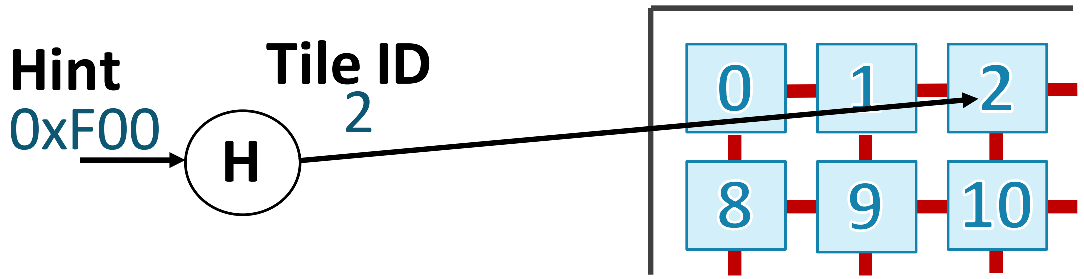


Localize most data accesses within a tile

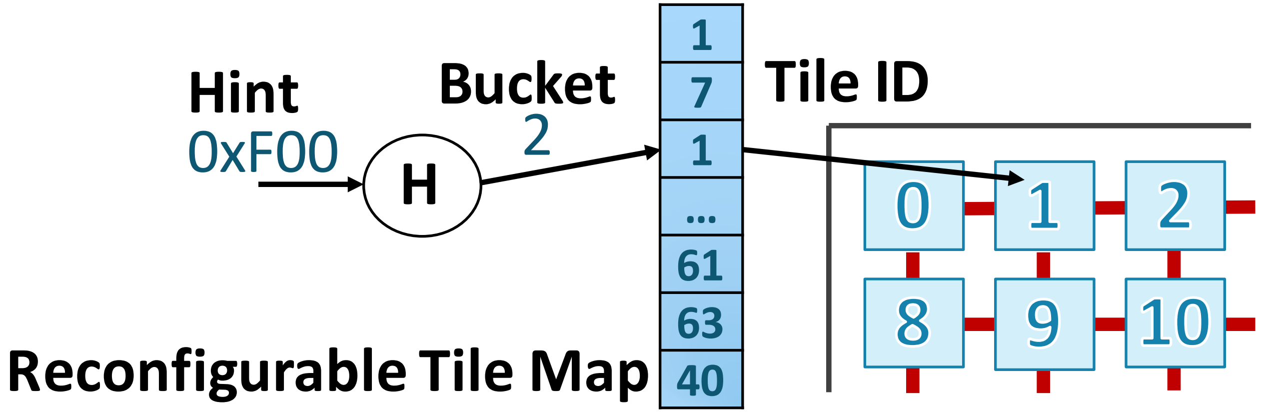
Serialize tasks likely to conflict

Load balance with a level of indirection

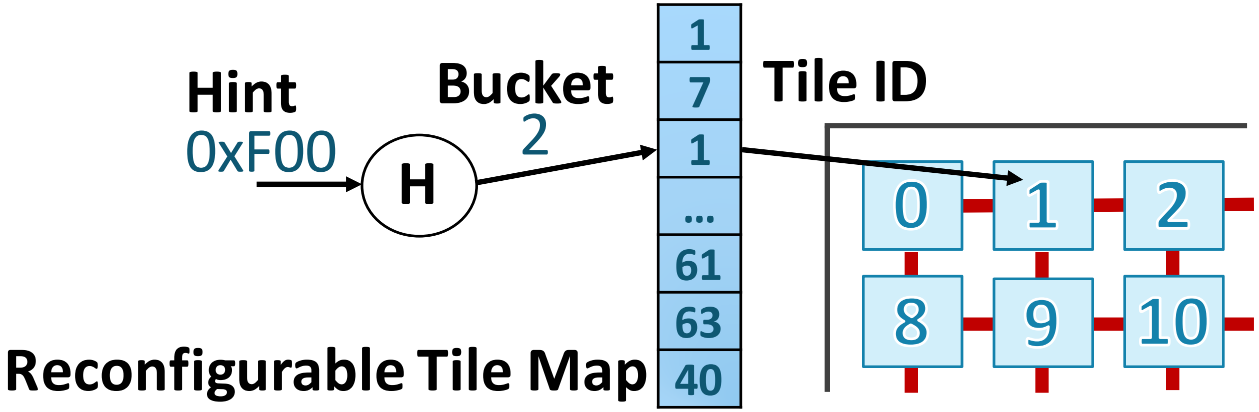
Static hint-to-tile mapping may cause **imbalance**



Instead, periodically **remap hints** across tiles to equalize load



“Load” is different for speculation



Non-speculative systems use **# queued tasks** as a proxy for load

When imbalanced, speculative systems often

- Don’t run out of work
- **Abort more work** or **strain speculation resources**

Remap hints to tiles to balance # of committed cycles per tile

Adding hints to applications is easy

```
void desTask(Timestamp ts, GateInput* input) {
  Gate* g = input->gate();
  bool toggledOutput = g.simulateToggle(input);
  if (toggledOutput) {
    // Toggle all inputs connected to this gate
    for (GateInput* i : g->connectedInputs())
      swarm::enqueue(desTask,
                     /*Timestamp*/ ts + delay(g, i),
                     /*Hint*/ i->gate()->id, i);
  }
}
```

One line of code to express the Gate ID as a Hint

Adding hints to applications is easy

Benchmark	Hint	Why?
des	Gate ID	Map tasks for same gate to same tile
nocsim	Router ID	Frequent intra-router communication
bfs, sssp, astar, color	Cache-line address	Several vertices reside on the same line
silo	(Table ID, primary key)	Each task accesses one database tuple
genome, kmeans	Multiple	

See the paper for more details!

Load balance reconfiguration algorithm

Choice of application hints

Relationship between task size and hint effectiveness

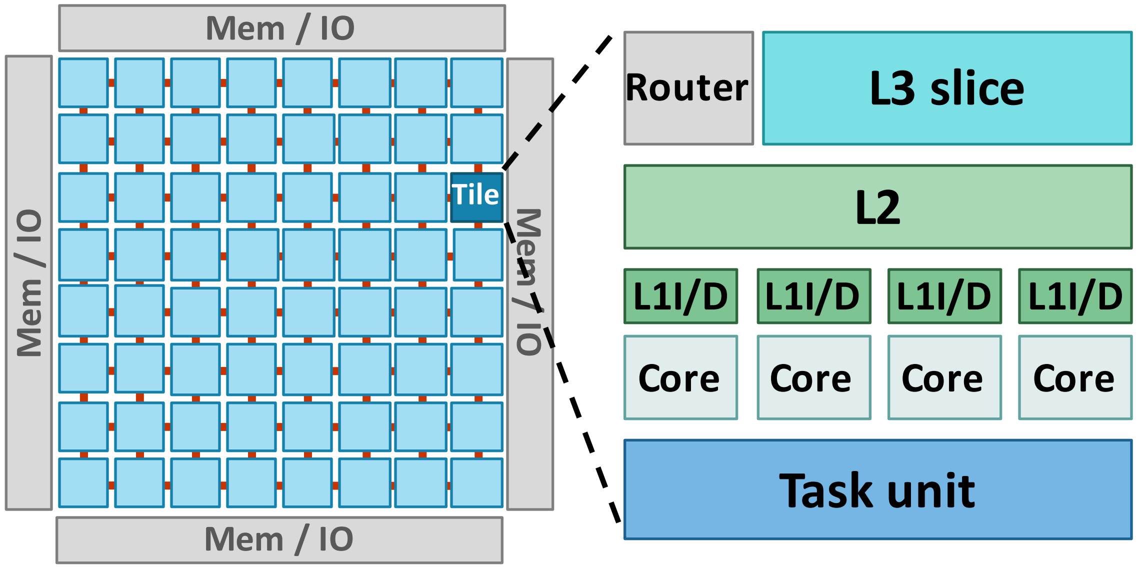
Evaluation

Methodology

Event-driven, Pin-based simulator

Scalability experiments from 1–256 cores
- Scaled-down systems have fewer tiles

Target system: 256-core, 64-tile chip



64 MB shared L3 (1MB/tile)

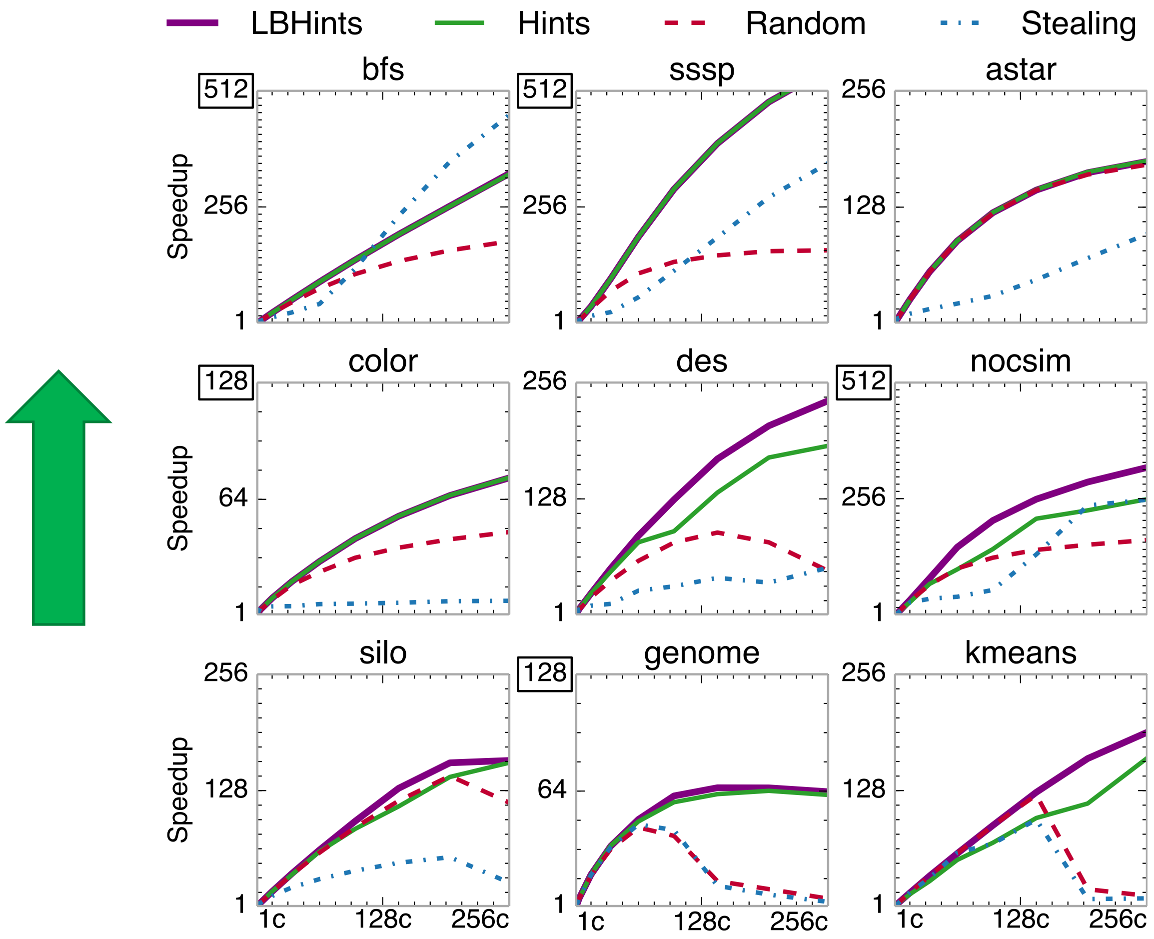
256 KB per-tile L2s

16 KB per-core L1s

In-order, single-issue, scoreboarded

16K task queue entries (64/core)
4K commit queue entries (16/core)

Hints make speculation practical on large-scale systems



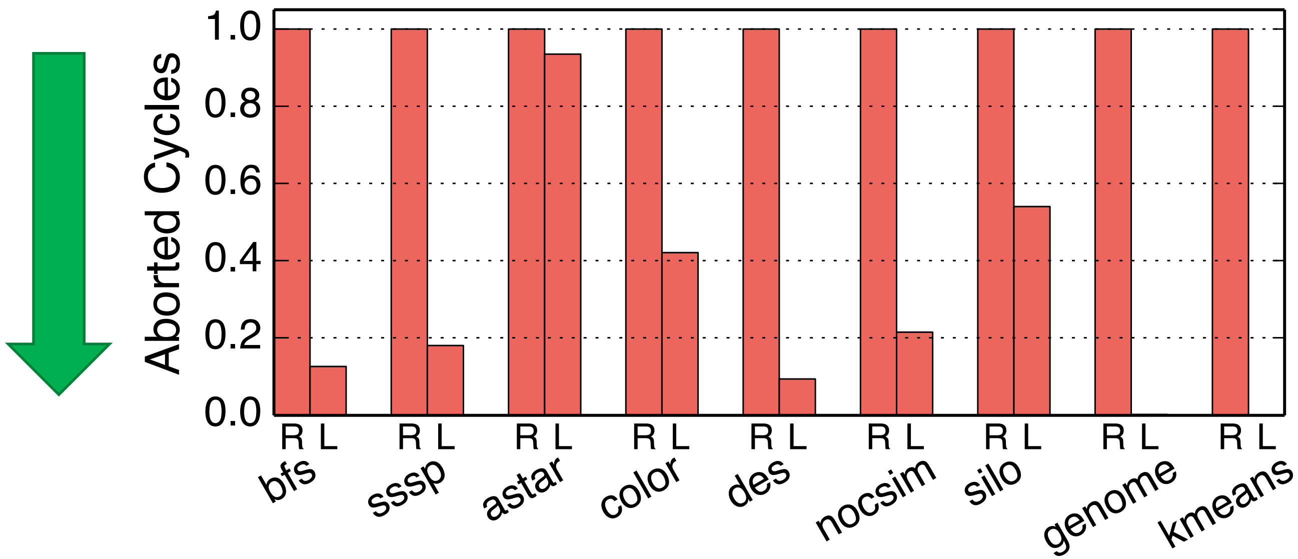
Load-Balanced Hints 3.3x faster than **Random** (**193x** gmean vs **58x**)

Load-Balanced Hints

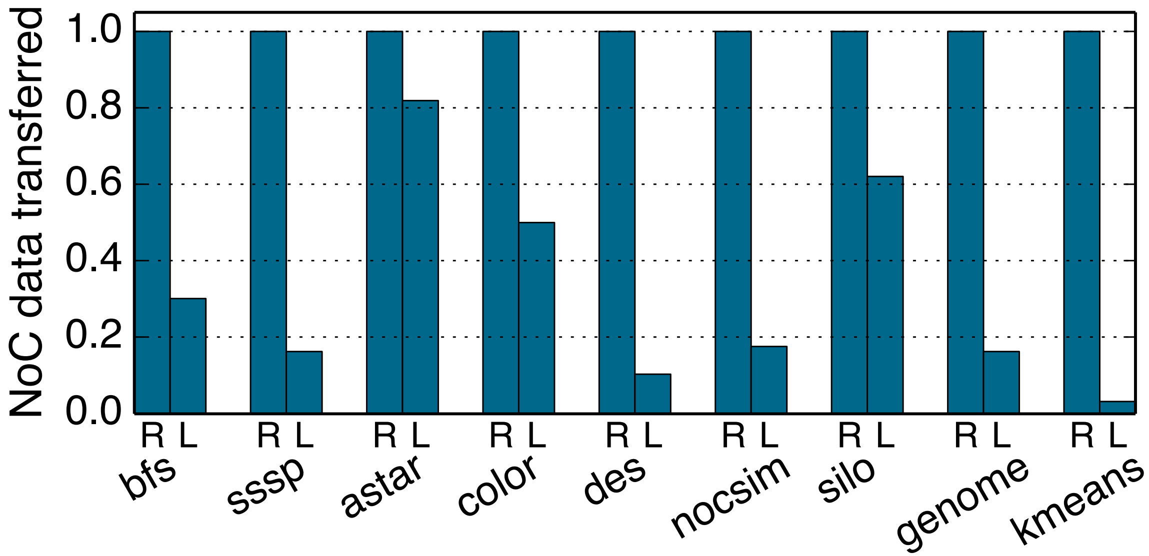
17% – 27% faster than **Hints**

Stealing is inconsistent across benchmarks

Hints make speculation more efficient



Reduce wasted work by 6.4x



Reduce network traffic by 3.5x

Conclusion

Speculative architectures must exploit locality to scale to 100s of cores

- Important to simplify parallel programming

Spatial Hints convey app-level knowledge to exploit cache locality

Hardware leverages hints by:

- Sending tasks likely to access the **same data to the same tile**
- **Serializing** tasks likely to conflict
- **Balancing work** in a locality-aware and speculation-friendly way

Our techniques make speculation practical on large-scale systems

Thank you! Questions?

Speculative architectures must exploit locality to scale to 100s of cores
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Our techniques make speculation practical on large-scale systems