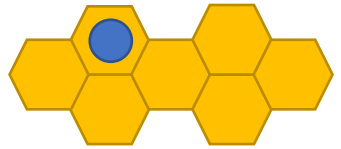
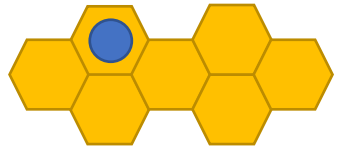
A Scalable Architecture for Reprioritizing Ordered Parallelism

Gilead Posluns, Yan Zhu, Guowei Zhang, Mark C. Jeffrey

ISCA 2022

Ordered algorithms use priority schedules





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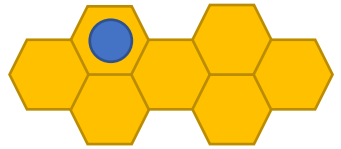

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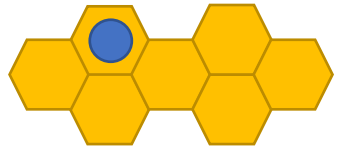
Priority schedules accelerate convergence

Dijkstra's SSSP

Breadth First Search

Residual Belief Propagation



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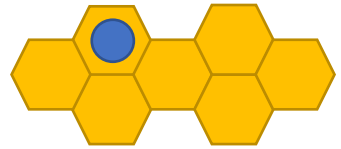
Priority schedules are correct

Minimum Spanning Forest

KCore

Set Cover

Maximal Independent Set



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Priority schedules accelerate convergence

Priority schedules are powerful, but hard to parallelize

Priority schedules are correct

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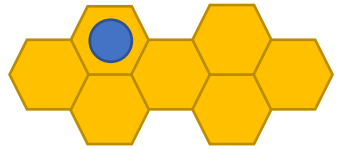
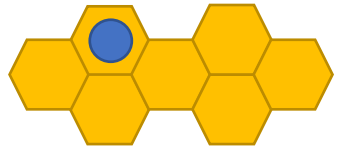


Hive parallelizes priority updates

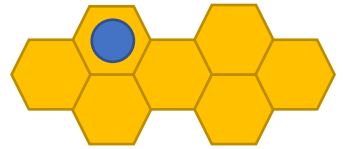
Hive builds on Swarm to provide a parallel **priority update** operation in speculative task-parallel hardware

Hive speculates eagerly on data, control, and **scheduler dependences**

Hive achieves >100x speedup over parallel software, and up to 2.8x over Swarm at 256 cores



Understanding Priority Updates



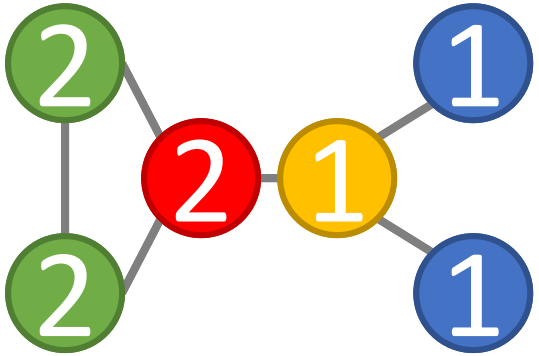
KCore requires priority updates

Max core of a vertex ≈ “importance” [Malliaros et al. VLDB ‘20]

To find: repeatedly remove lowest degree vertex

```
PriorityQueue pq;
for (int v: G.V)
  pq.enqueue(v, G.degree[v])
while (!pq.empty()) {
  int v, int prio = pq.dequeueMin();
  coreness[v] = prio;
  for (int nbr : G.edges[v])
    pq.decrementPrio(nbr)
}}
```

Input Graph



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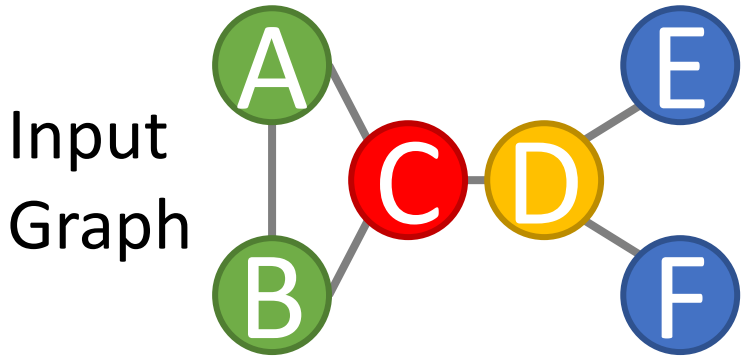

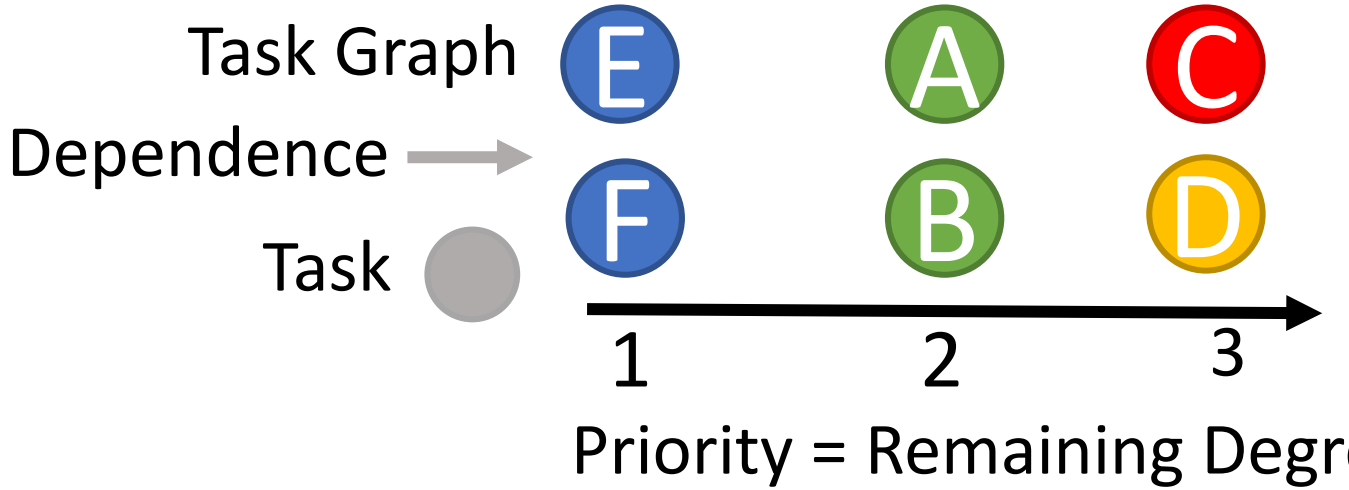

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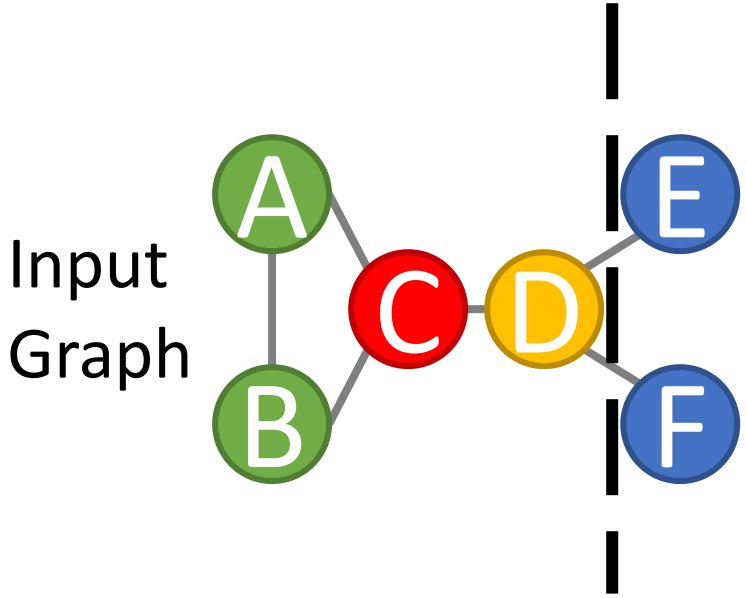

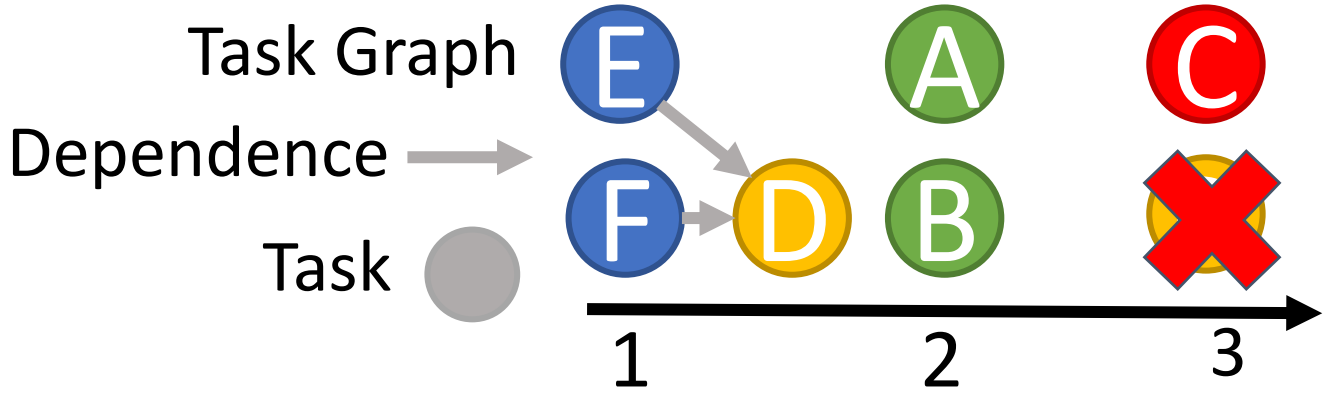

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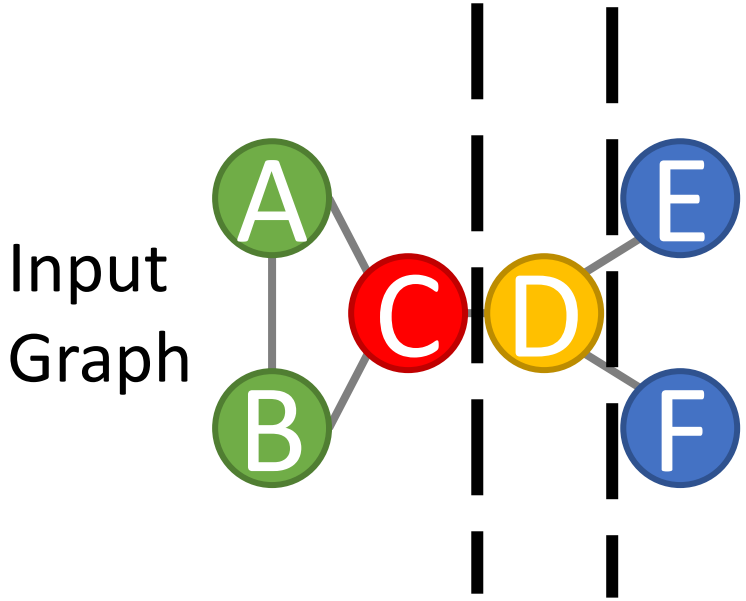

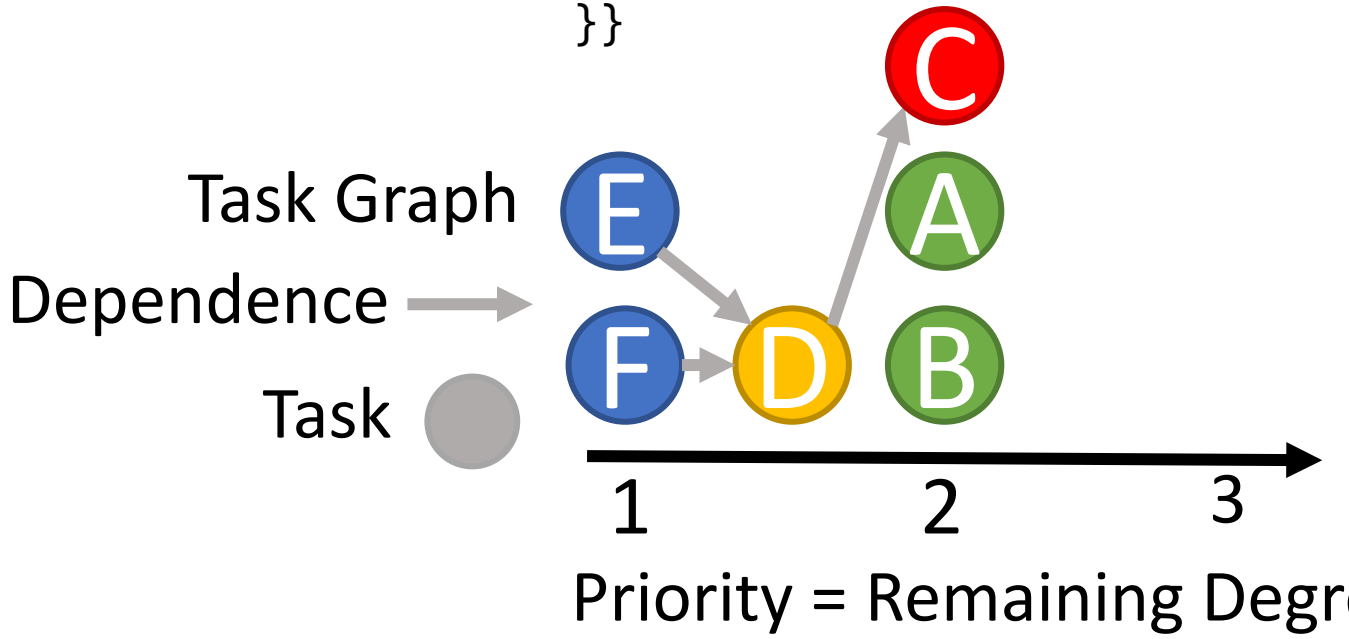

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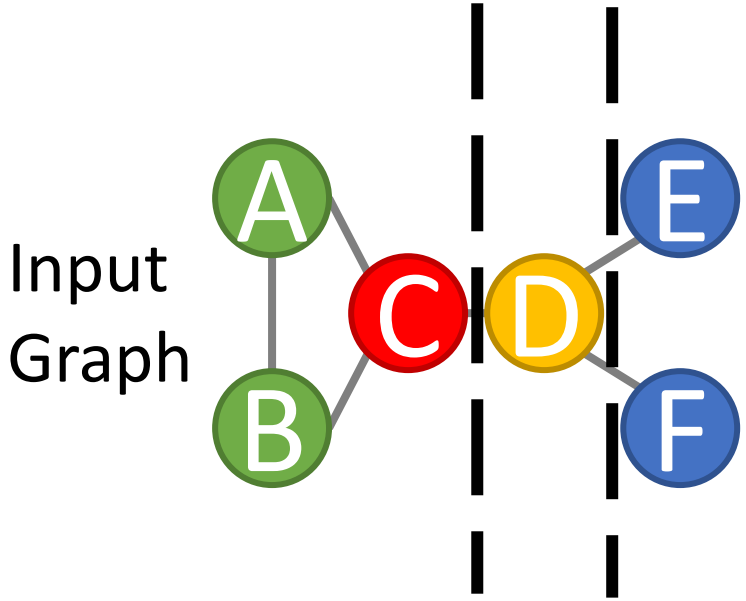

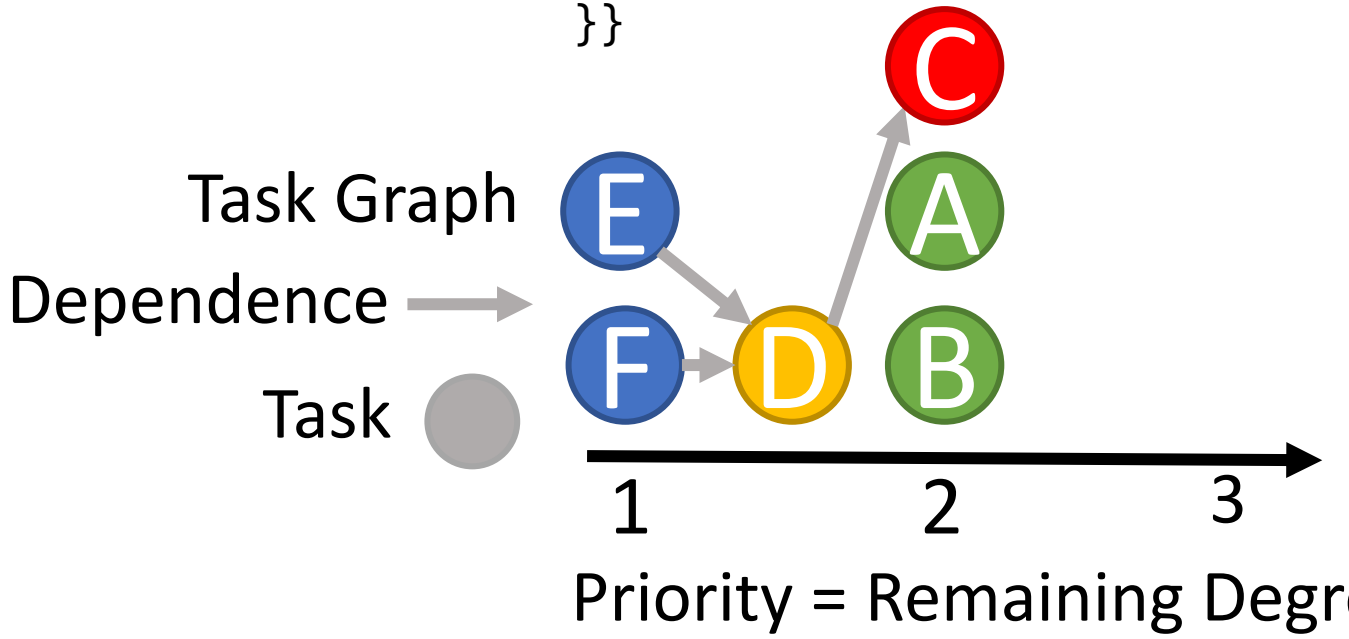

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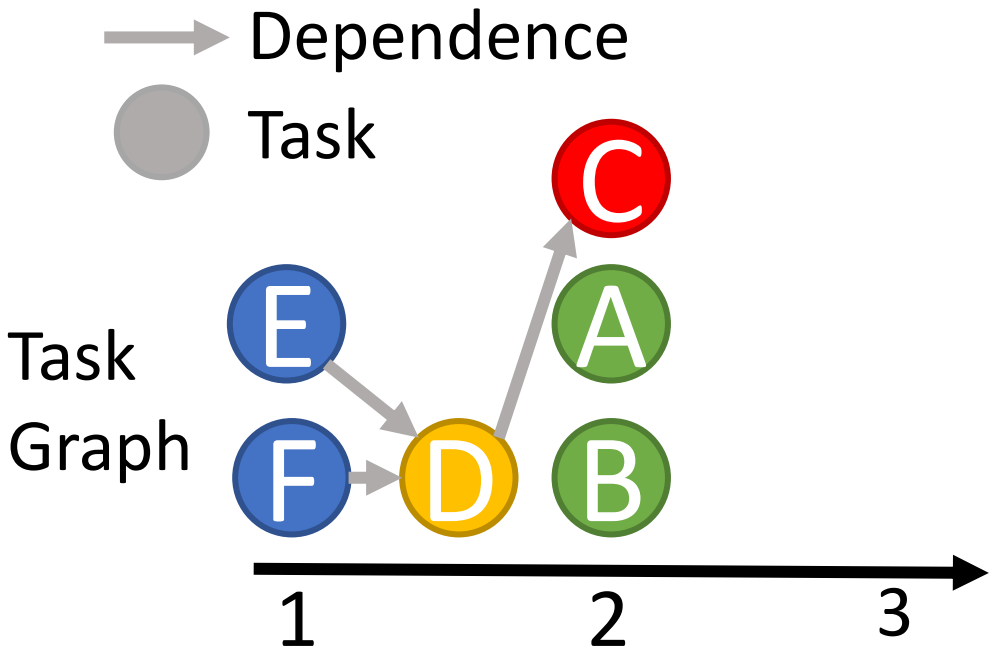
Where’s the parallelism in KCore?



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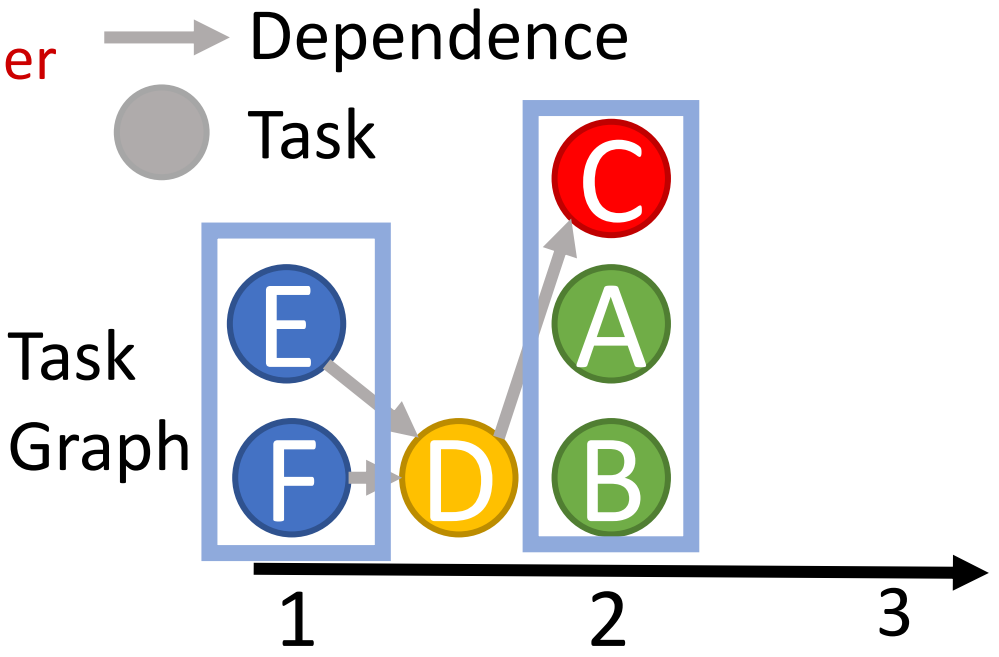

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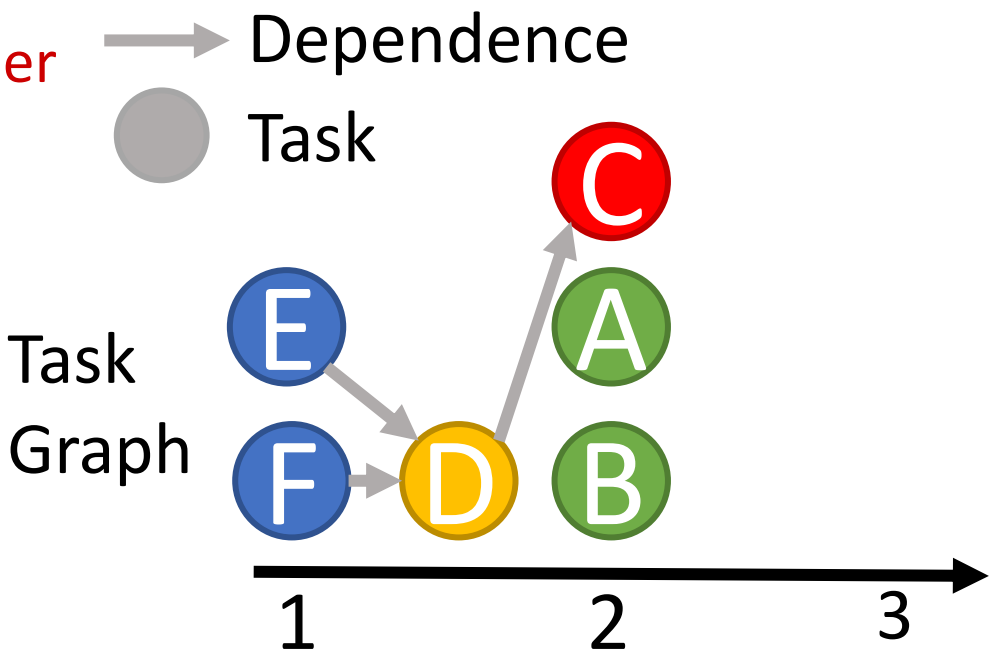
  - Can always find parallelism
  - loses efficiency as it scales
  - Not always correct



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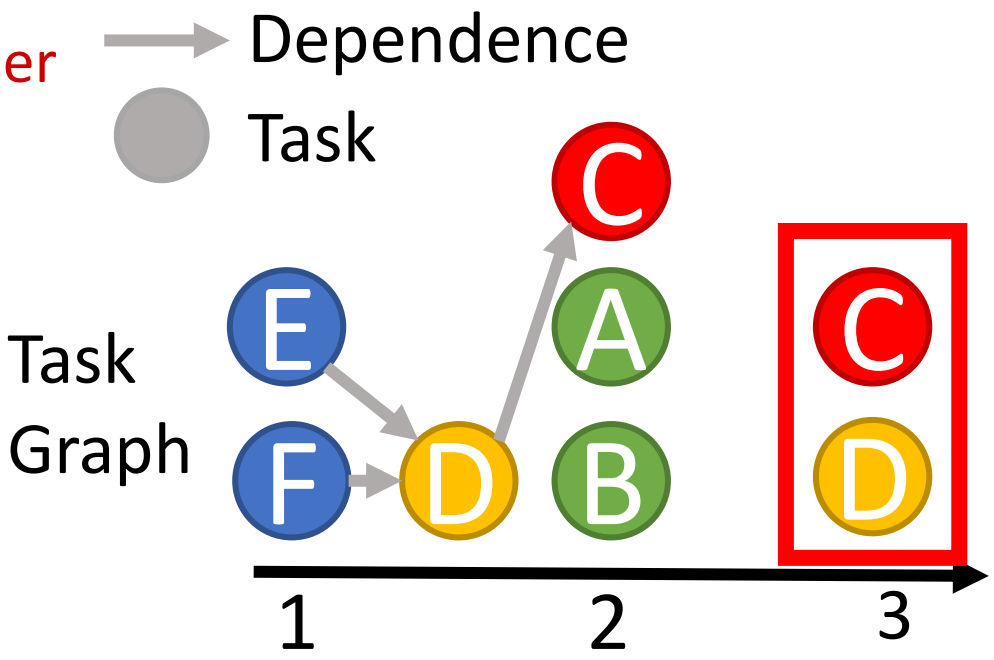

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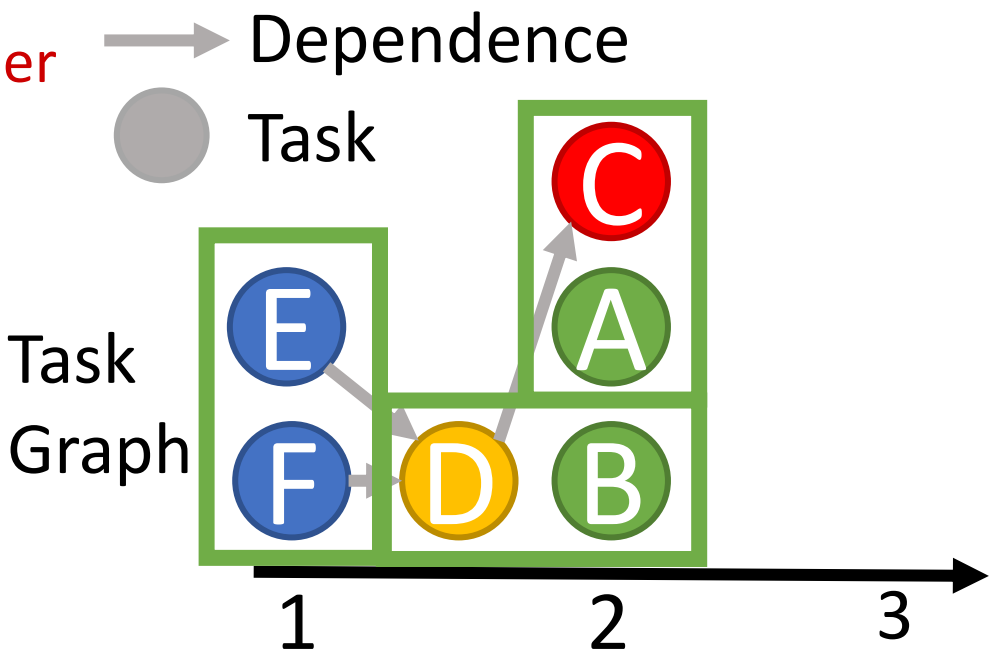
  - Existing HW systems do not support priority updates



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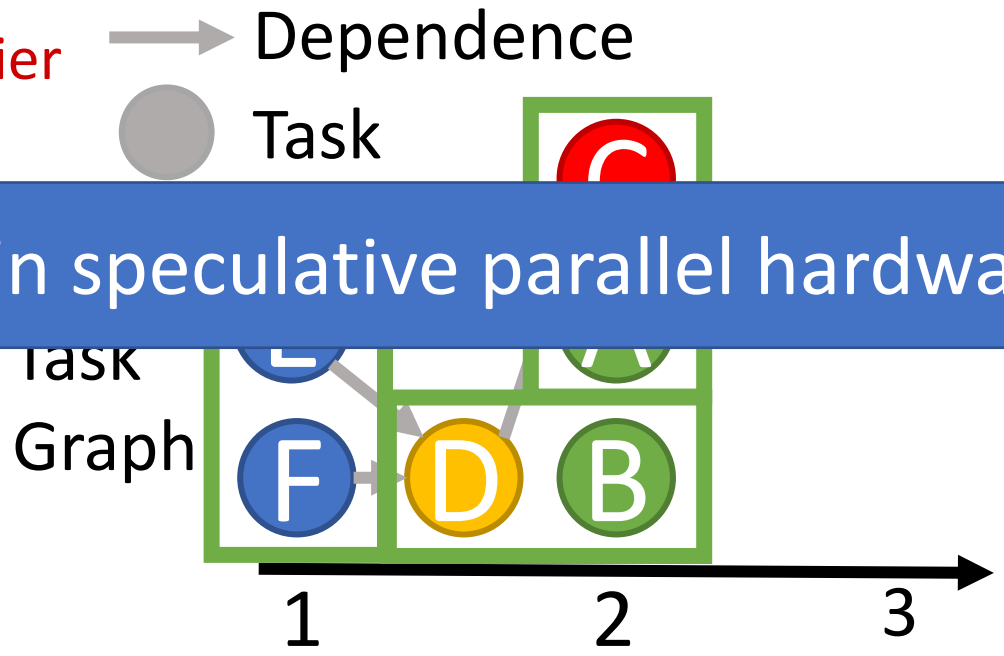
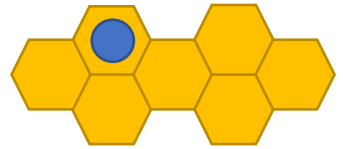
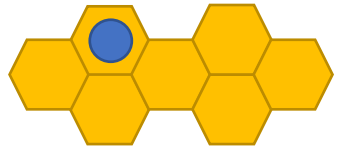
Our goal is to support priority updates in speculative parallel hardware





Swarm [Jeffrey et al. MICRO'15] speculates without updates

Task-Based Execution Model



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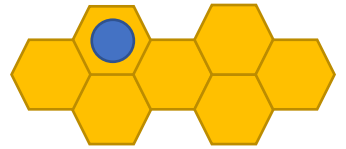
- Programs consist of timestamp-ordered tasks
- Tasks appear to execute in timestamp order



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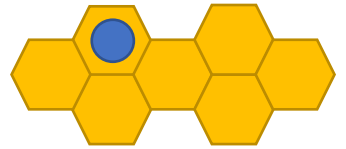

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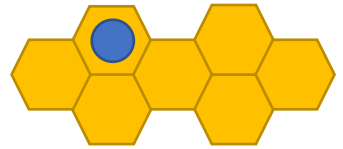
- Programs consist of timestamp-ordered tasks
- Tasks appear to execute in timestamp order
- Scheduler is **only** accessed with enqueues

```
swarm::enqueue(
      fn,  //what to do
      ts,  //when to do it
      args //what to do it with);
```



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Swarm's execution model does not support priority updates

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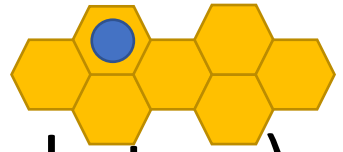

Swarm KCore is inefficient (i.e., without updates)

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Manual priority tracking

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Early exit for **moot** tasks

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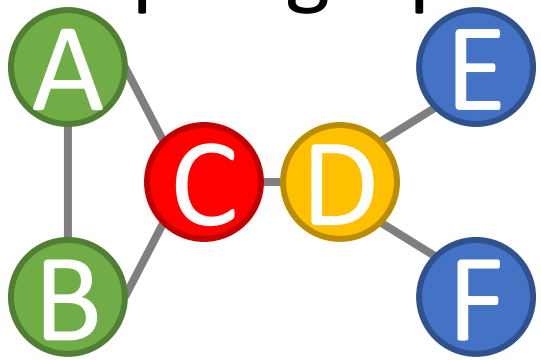
Manual priority tracking

Tasks that exit early are **moot**: they might as well not run at all

Early exit for **moot** tasks

Updateable schedules are efficient

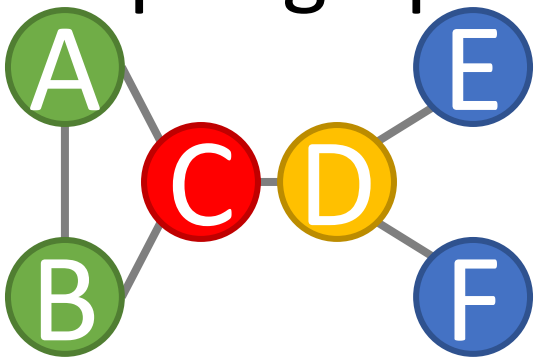
Input graph

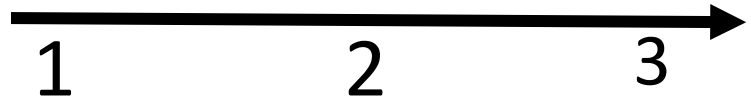


Updateable schedules are efficient

Updateable Task Graph

Input graph





Priority = Remaining Degree

Updateable schedules are efficient

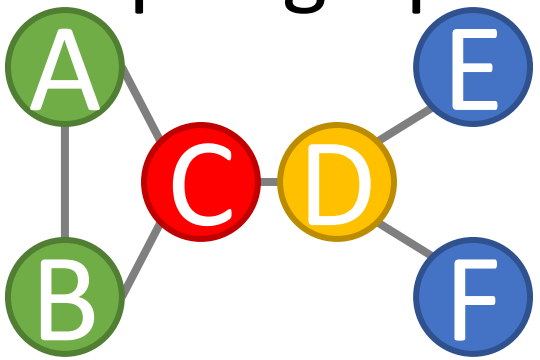
Swarm Task Graph

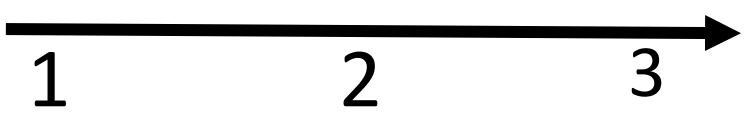
Dependence

Task

Updateable Task Graph

Input graph





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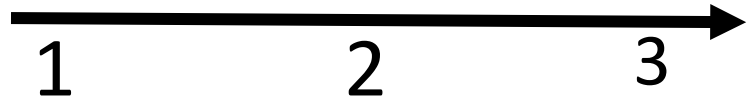

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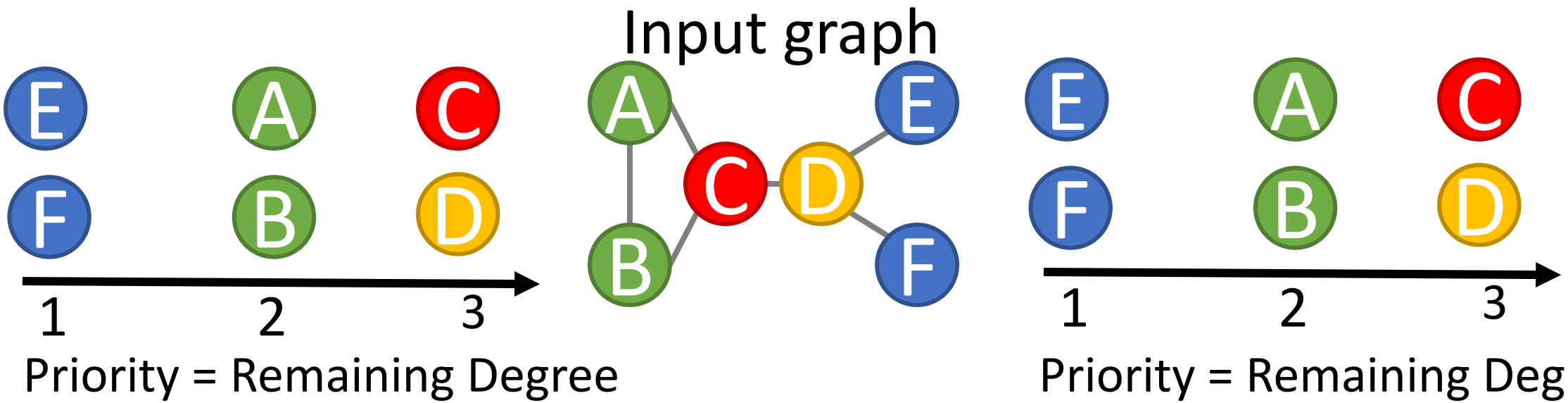

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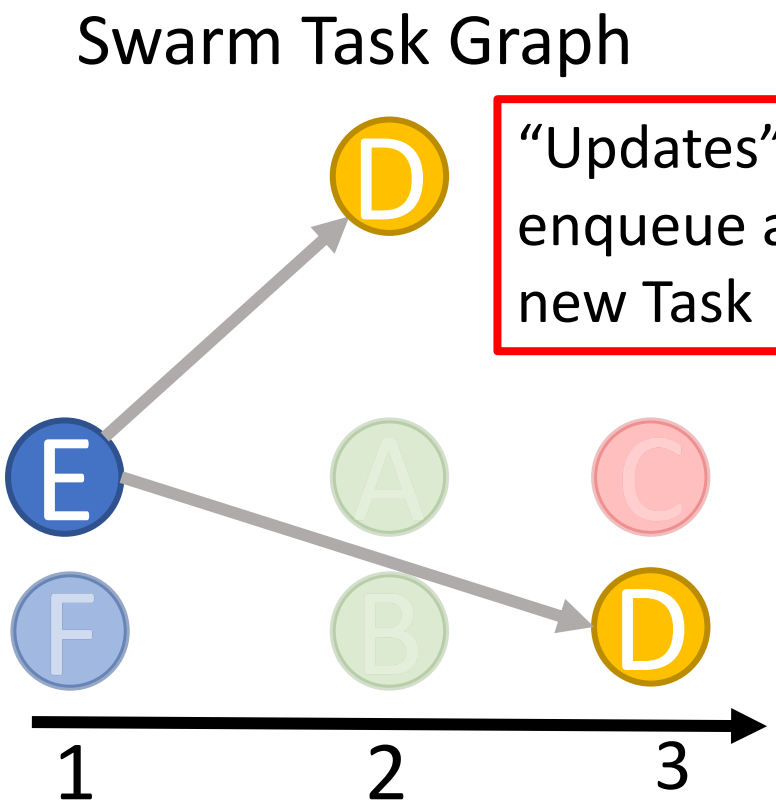
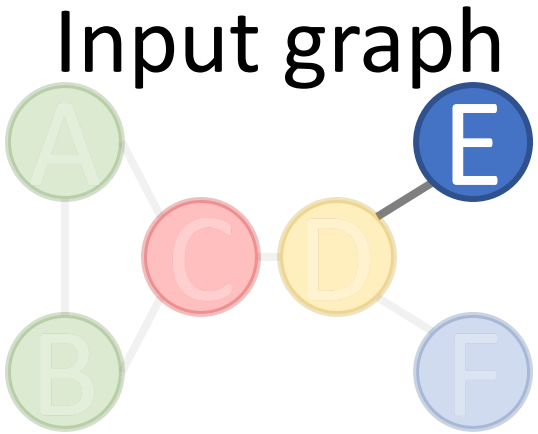
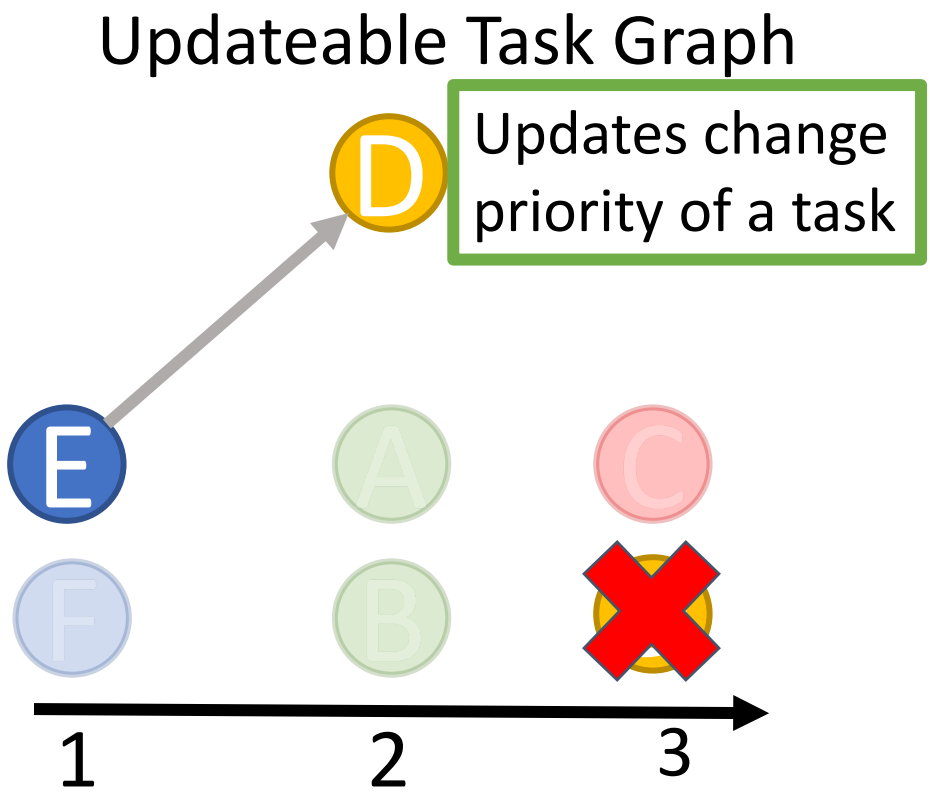


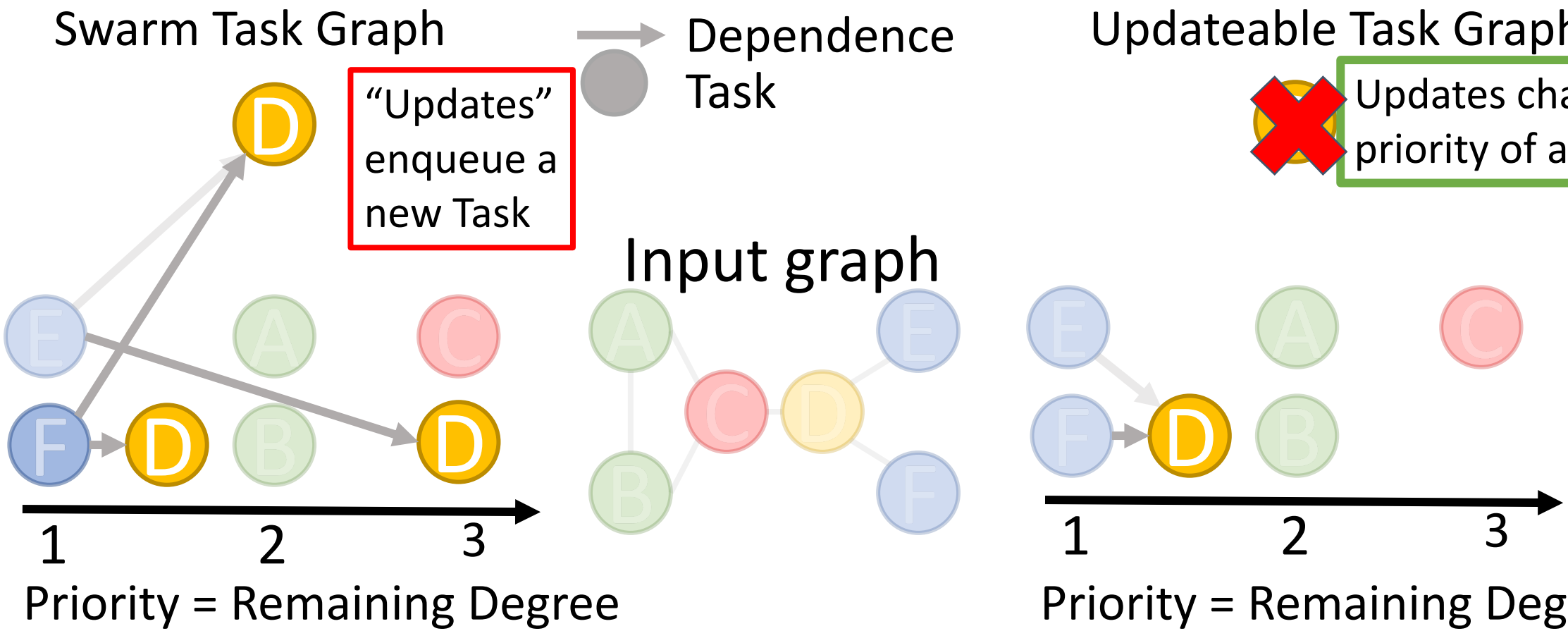
Dependence Task

"Updates" enqueue a new Task





Updateable schedules are efficient



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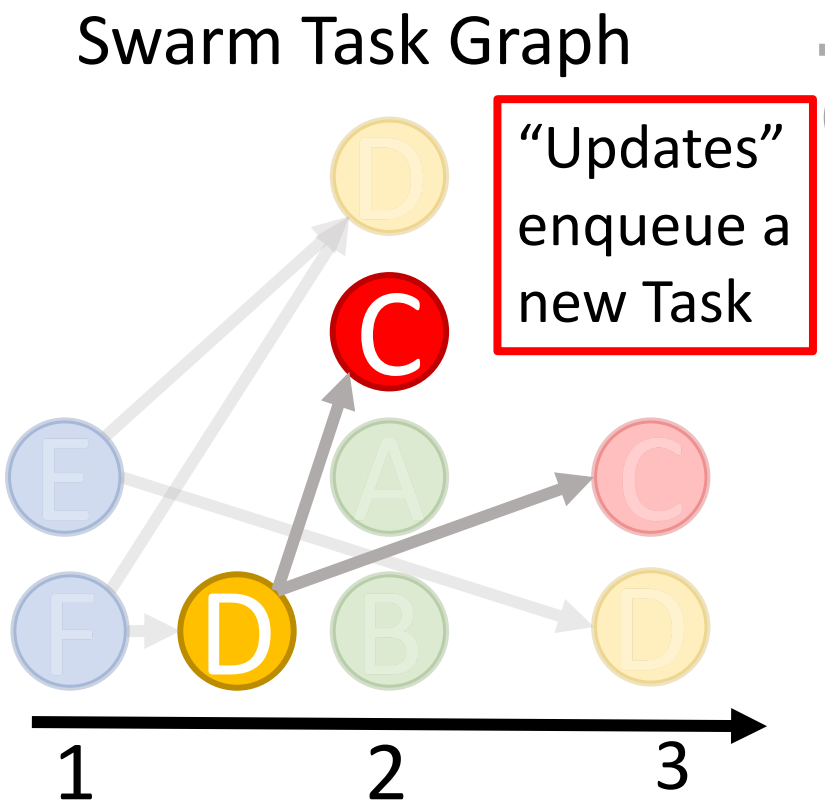
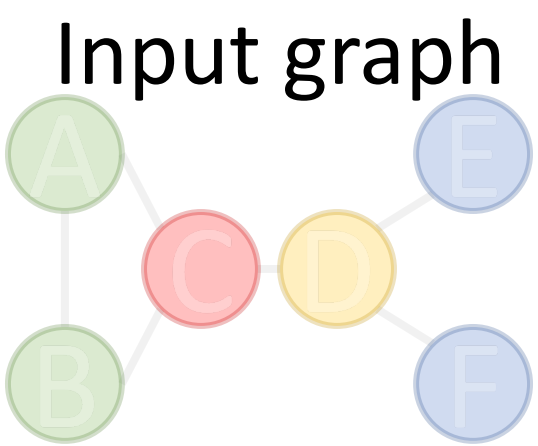
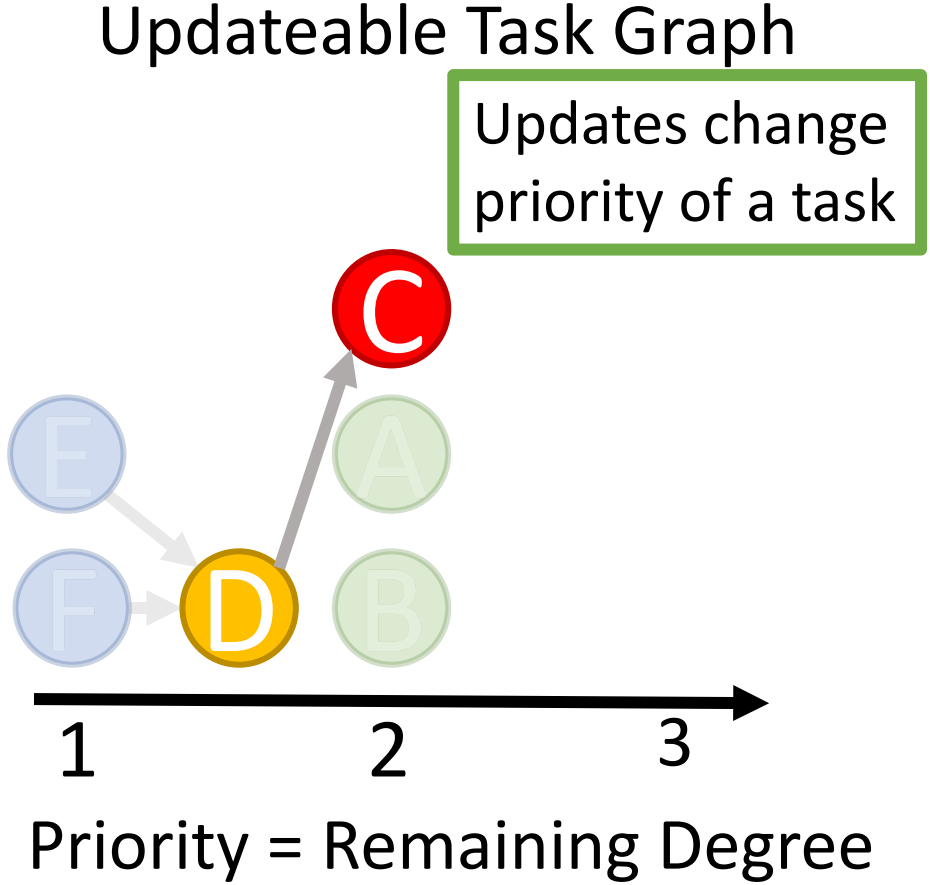
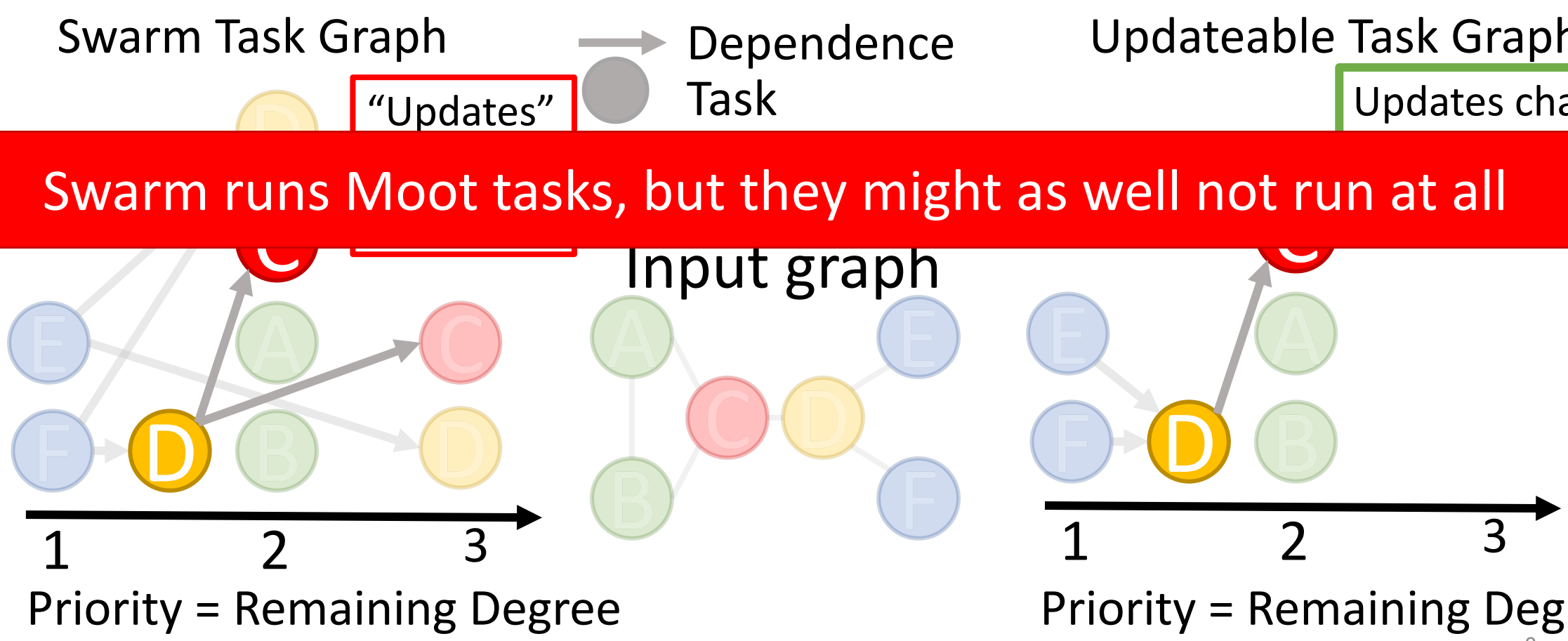




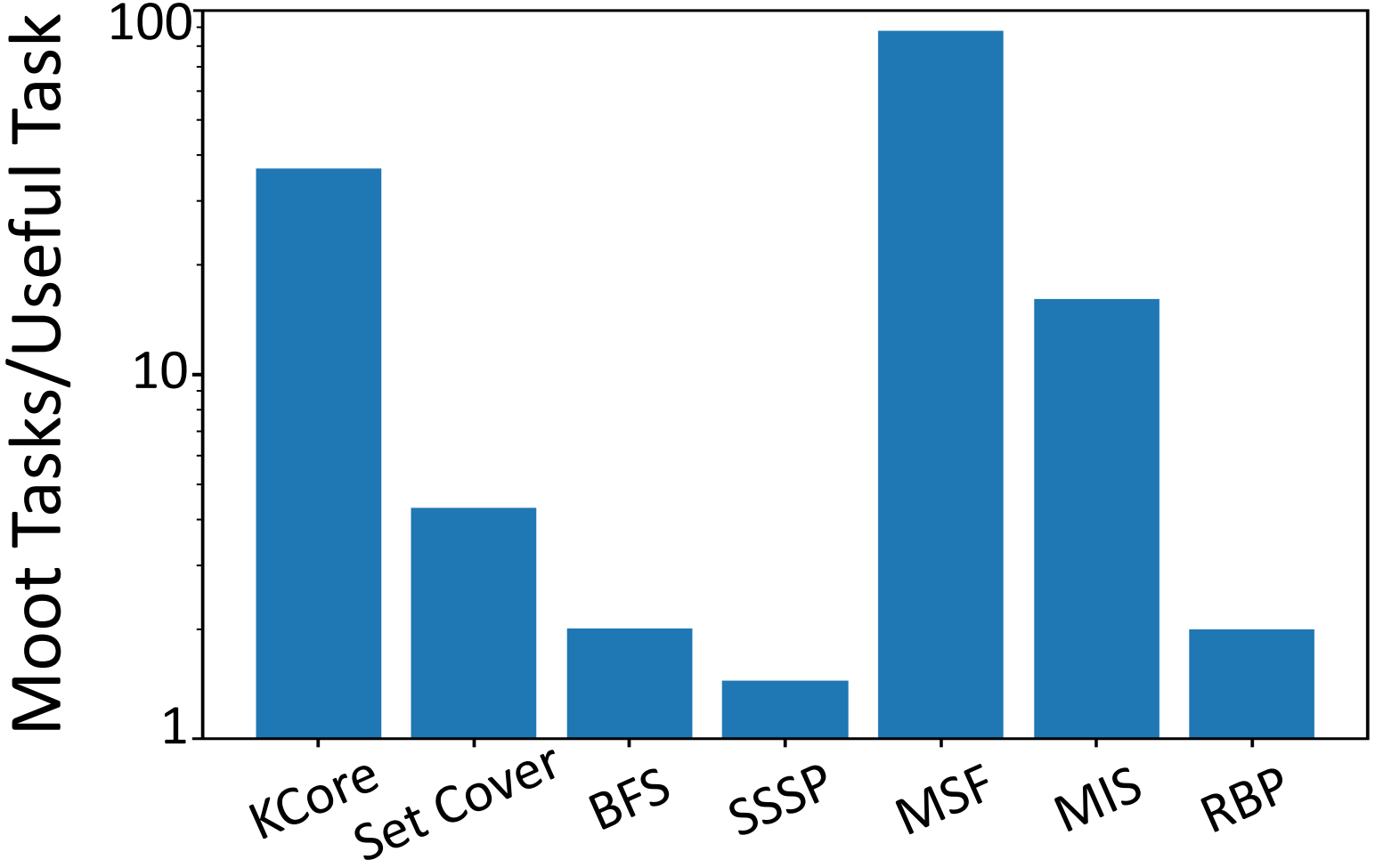


Updateable schedules are efficient

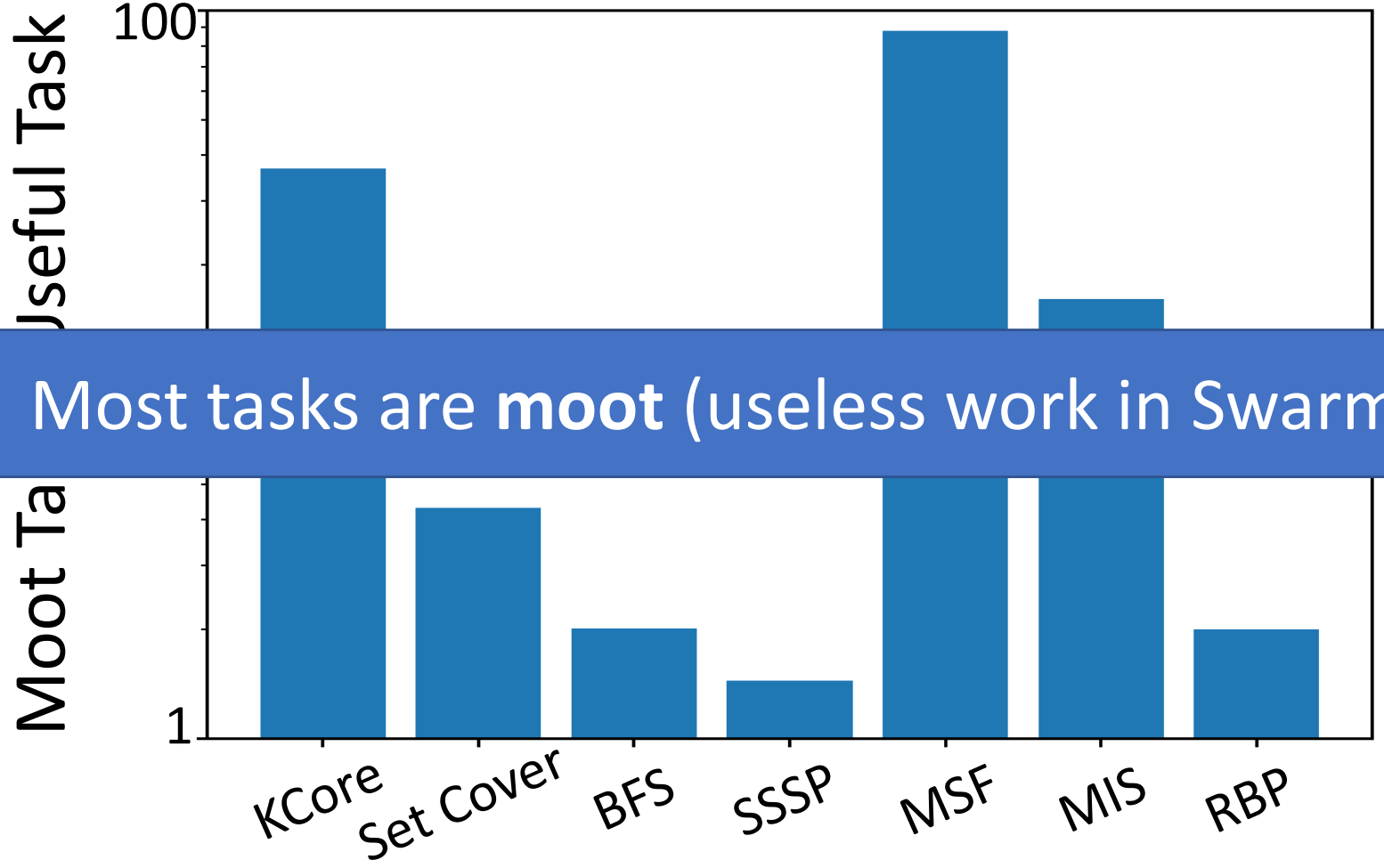
Enqueue-only schedule has 3 more tasks than updateable schedule



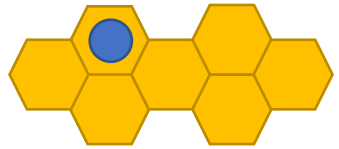
Moot tasks outnumber useful dequeues



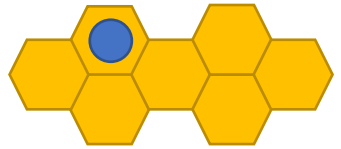
Moot tasks outnumber useful dequeues



Most tasks are **moot** (useless work in Swarm)



The Hive Execution Model



Understanding Hive tasks and objects

```
void removeV(int v, Timestamp ts) {
  coreness[v] = ts;
  for (int nbr : G.edges[v]) {
    Timestamp prev = hive::getTS(nbr);
    if (prev > ts)
      hive::update(&removeV, nbr, prev-1);
}}
```

Understanding Hive tasks and objects

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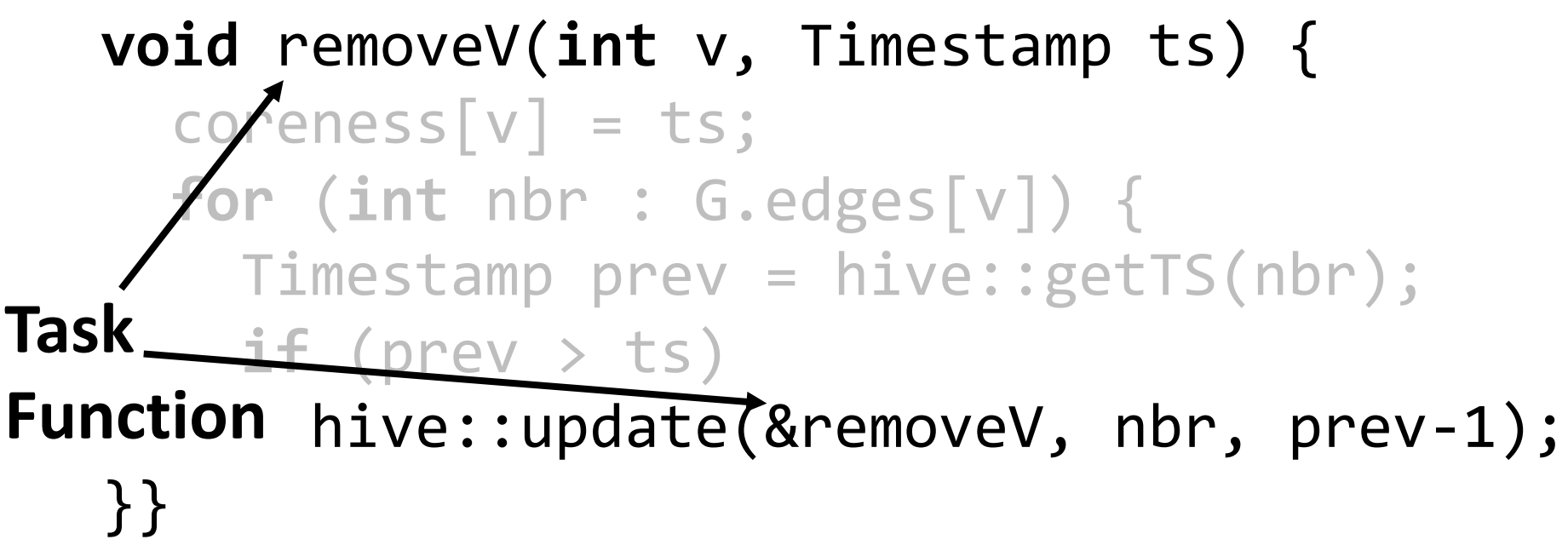
Understanding Hive tasks and objects

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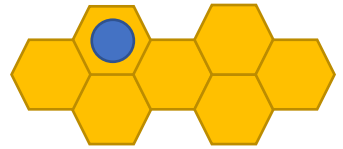
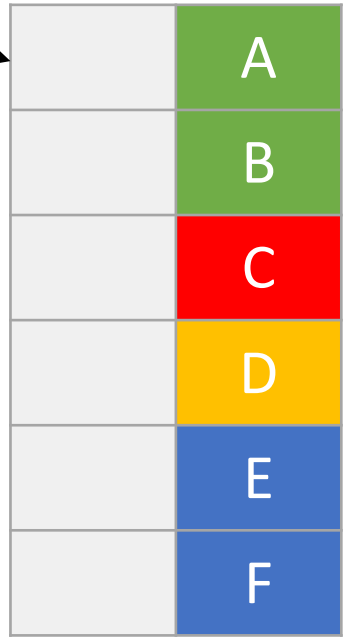
  }}
```



Understanding Hive tasks and objects

Object

Object Table




```
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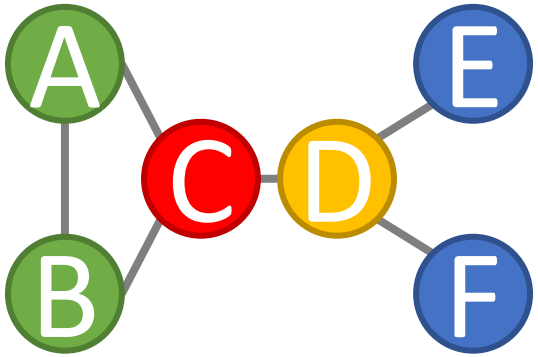
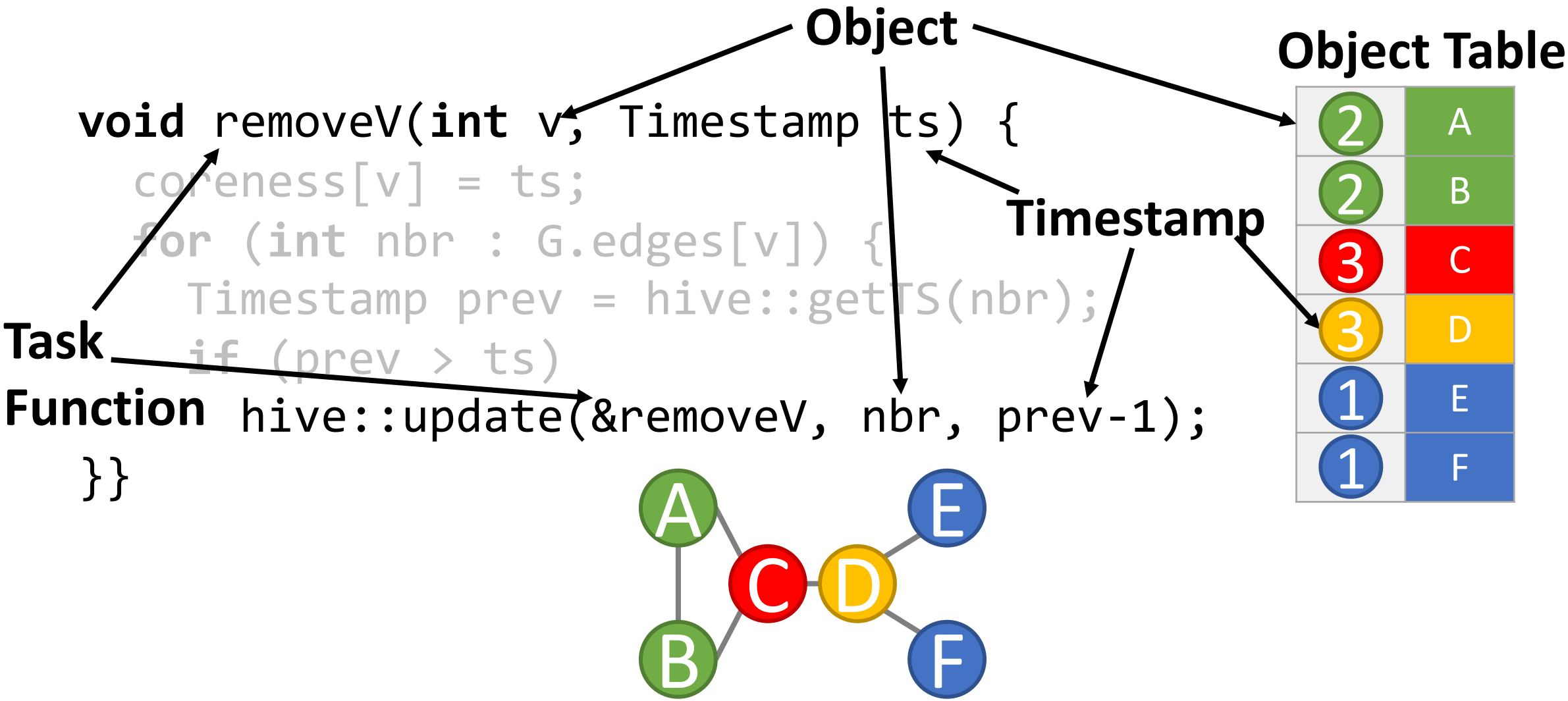
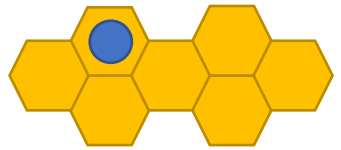
    if (prev > ts)
      hive::update(&removeV, nbr, prev-1);
  }}
```

Task Function



Understanding Hive tasks and objects





Understanding Hive tasks and objects

Object

Object Table

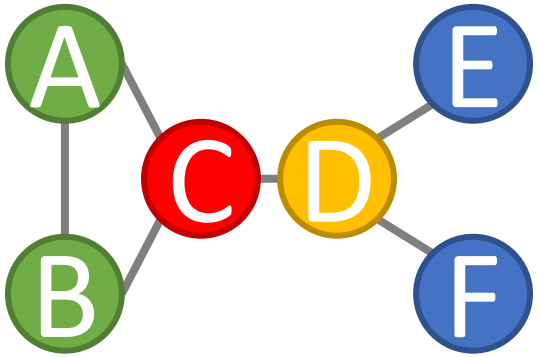
```
void removeV(int v, Timestamp ts) {
  coreness[v] = ts;
  for (int nbr : G.edges[v]) {
    if (prev > ts)
      hive::update(&removeV, nbr, prev-1);
  }}
```

Timestamp

Task Function

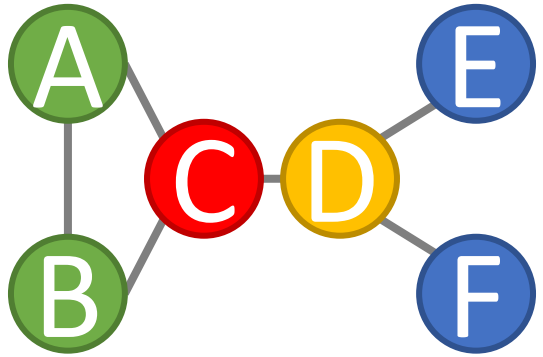
Update binds a task to an object and schedules it to run

2	A
2	B
1	E
1	F



Updating an occupied Hive object

```
void removeV(int v, Timestamp ts) {
  coreness[v] = ts;
  for (int nbr : G.edges[v]) {
    Timestamp prev = hive::getTS(nbr);
    if (prev > ts)
      hive::update(&removeV, nbr, prev-1);
}}
```



Object Table

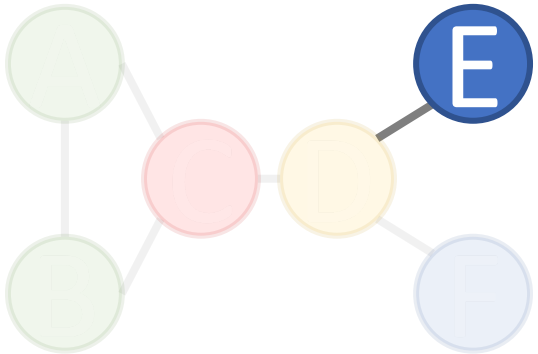
2	A
2	B
3	C
3	D
1	E
1	F

Updating an occupied Hive object

```
void removeV(int E, Timestamp ts) {
  coreness[E] = ts;
  for (int D : G.edges[E]) {
    Timestamp prev = hive::getTS(D);
    if (prev > ts)
      hive::update(&removeV, D, prev-1);
}}
```

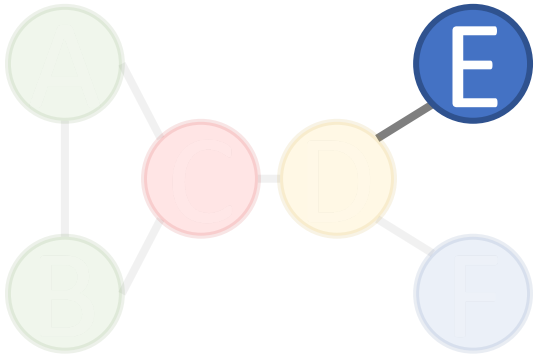
Object Table

2	A
2	B
3	C
3	D
1	E
1	F



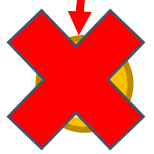
Updating an occupied Hive object

```
void removeV(int E, Timestamp ts) {
  coreness[E] = ts;
  for (int D : G.edges[E]) {
    Timestamp prev = hive::getTS(D);
    if (prev > ts)
      hive::update(&removeV, D, prev-1);
}}
```



Object Table

2	A
2	B
3	C
2	D
1	E
1	F

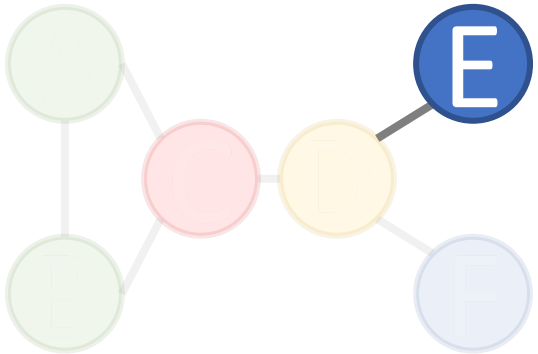


Moot

Updating an occupied Hive object

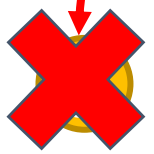
```
void removeV(int E, Timestamp ts) {
  coreness[E] = ts;
  for (int D : G.edges[E]) {
    if (prev > ts)
      hive::update(&removeV, D, prev-1);
}}
```

Hive doesn't waste time or space on **moot** tasks



Object Table

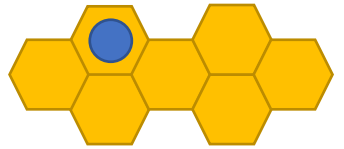
2	A
2	B
1	E
1	F



Moot

Hive supports many programming patterns

Benchmark	Increment	UpdateMin	Cancel	Update
KCore	✓			
Set Cover	✓			
Astar				
Breadth First Search				
SSSP				
Minimum Spanning Forest				
Maximal Independent Set				
Maximal Matching				
Residual Belief Propagation				



Hive supports many programming patterns

Benchmark	Increment	UpdateMin	Cancel	Update
KCore	✓			
Set Cover	✓	✓		
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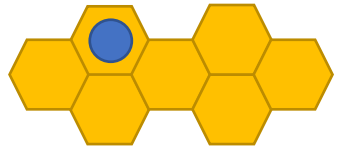
Breadth First Search		✓		
SSSP		✓		
Minimum Spanning Forest		✓	✓	
Maximal Independent Set			✓	
Maximal Matching			✓	
Residual Belief Propagation				✓



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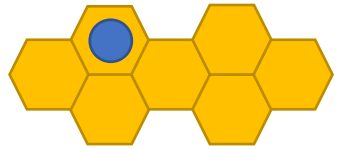
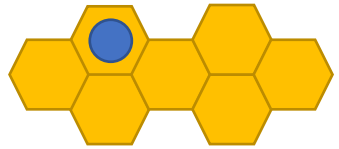
Breadth First Search		✓		
SSSP		✓		
Minimum Spanning Forest		✓	✓	
Maximal Independent Set			✓	
Maximal Matching			✓	
Residual Belief Propagation				✓

No Priority Queue in Sequential Implementation



Parallelizing Priority Updates



Hive speculates to run tasks in parallel

For each task, Hive speculates that:

- Eager data speculation: Predecessors have already performed their writes
- Eager control speculation: Its parent will not abort
- Eager scheduler speculation: It will not be replaced by an update

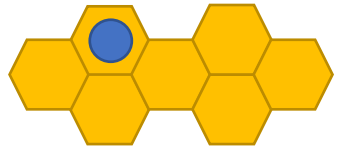
Hive speculates to run tasks in parallel

For each task, Hive speculates that:

- Eager data speculation: Predecessors have already performed their writes
- Eager control speculation: Its parent will not abort

The same as Swarm [Jeffrey et al. MICRO'15]

- Eager scheduler speculation: It will not be replaced by an update

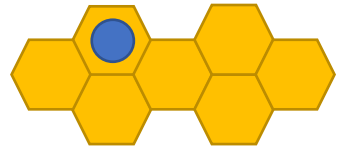


Priority updates are scheduler dependences

- The scheduler dependence is old
  - Found in self-modifying code [Wilkes and Renwick. ‘49]

```
STR R5, [PC, #4]
ADD R1, R1, R1
```

- Created by priority updates
  - When a task replaces a later-scheduled task, it creates a scheduler dependence
- Can be predicated into data and control dependences
  - Moot tasks are like predicated instructions in straight-line code



Priority updates are scheduler dependences

- The scheduler dependence is old
  - Found in self-modifying code [Wilkes and Renwick. ‘49]
- Created by priority updates

```
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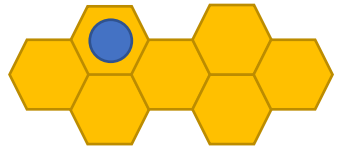
ADD R1, R1, R1
```

Updates have a different dependence, they need different speculation

- Can be predicated into data and control dependences
  - Moot tasks are like predicated instructions in straight-line code

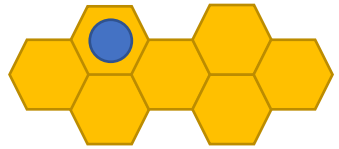
Scheduler speculation: Task versioning and Mootness detection



- Maintain multiple versions of each task
  - 1 for each speculative update + up to 1 non-speculative
- 1 task version is speculatively valid, all others are speculatively Moot
  - Speculatively Moot task versions are not runnable
- When Mootness becomes non-speculative, discard the Moot version

- Mootness can detected by comparing timestamps of parents

Scheduler speculation:
Task versioning and Mootness detection

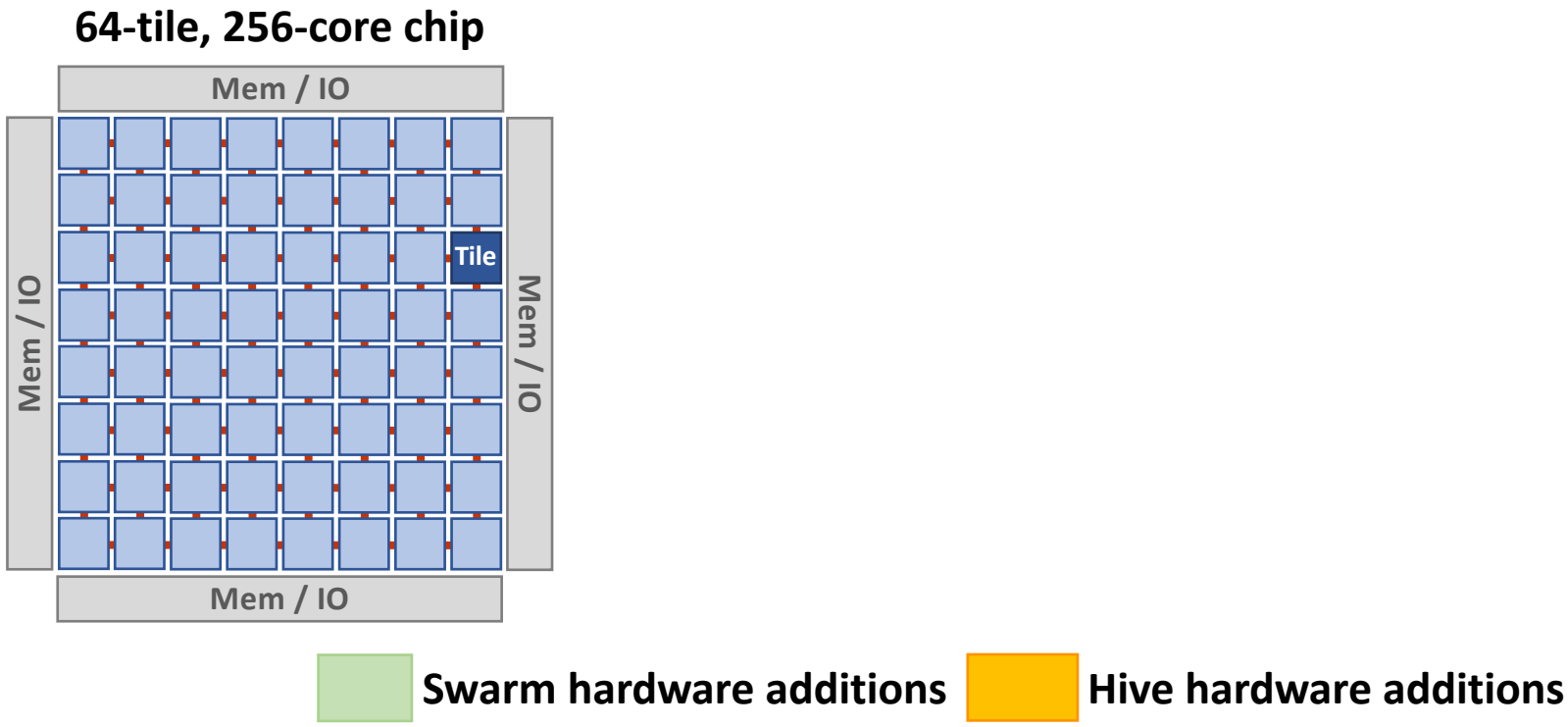


- Maintain multiple versions of each task
  - 1 for each speculative update + up to 1 non-speculative
- 1 task version is speculatively valid, all others are speculatively Moot
- When Mootness becomes non-speculative, discard the Moot version

Hive avoids running moot tasks and reduces their speculative state

- Mootness can detected by comparing timestamps of parents

Hive extends the Swarm architecture



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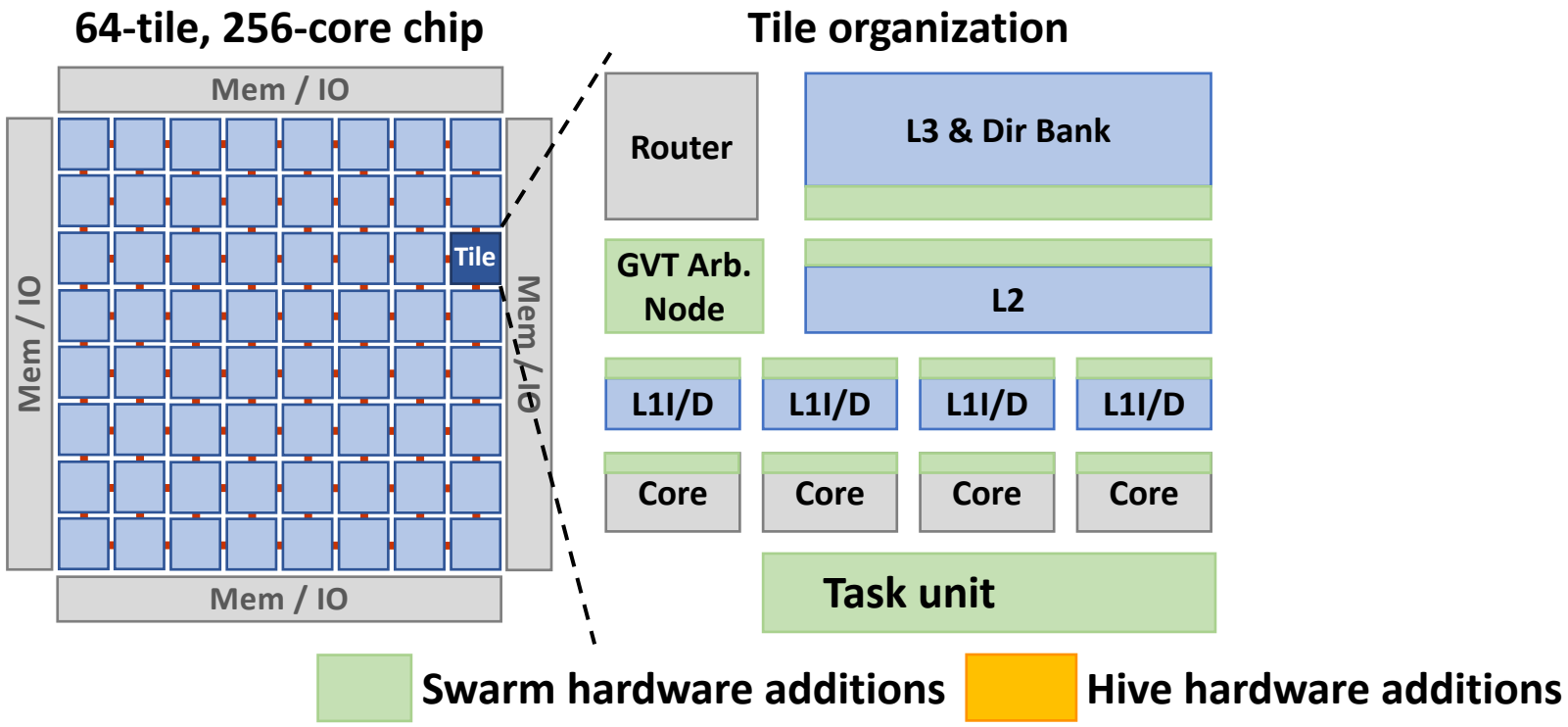
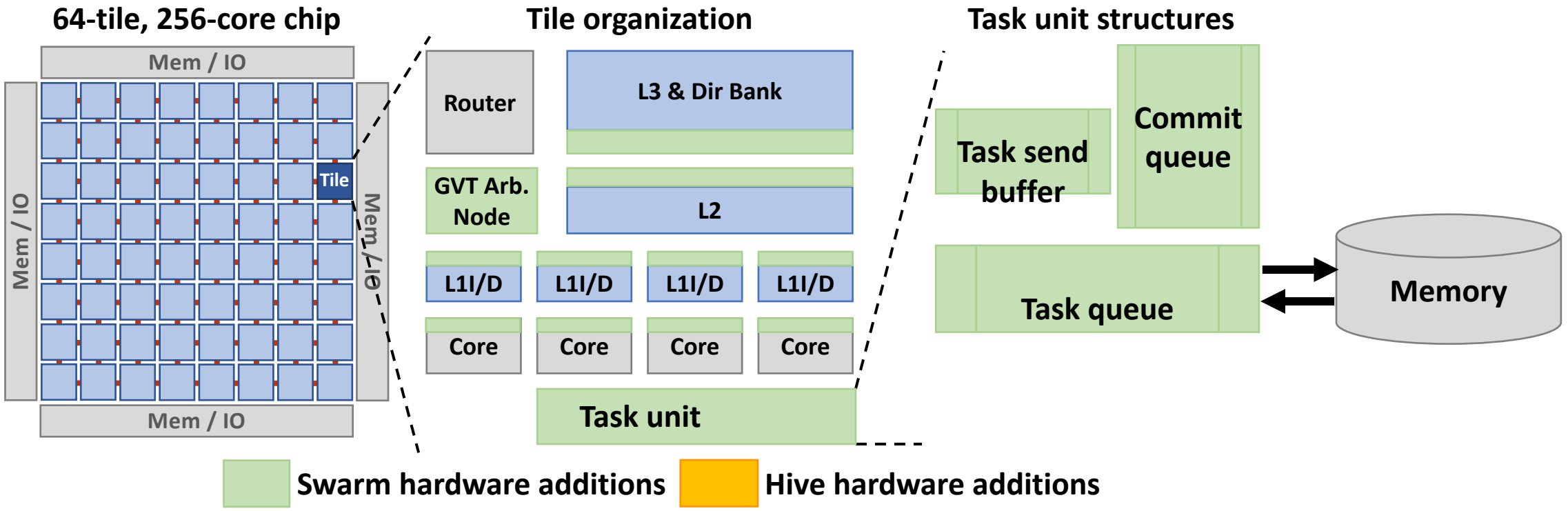


Hive extends the Swarm architecture



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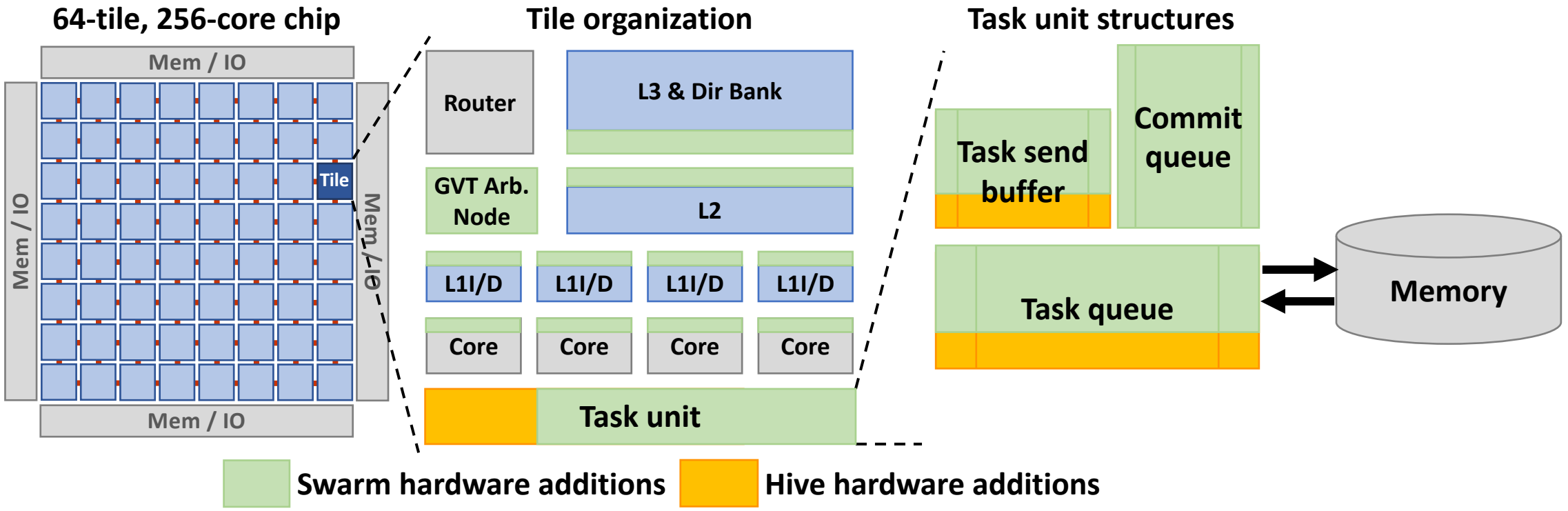

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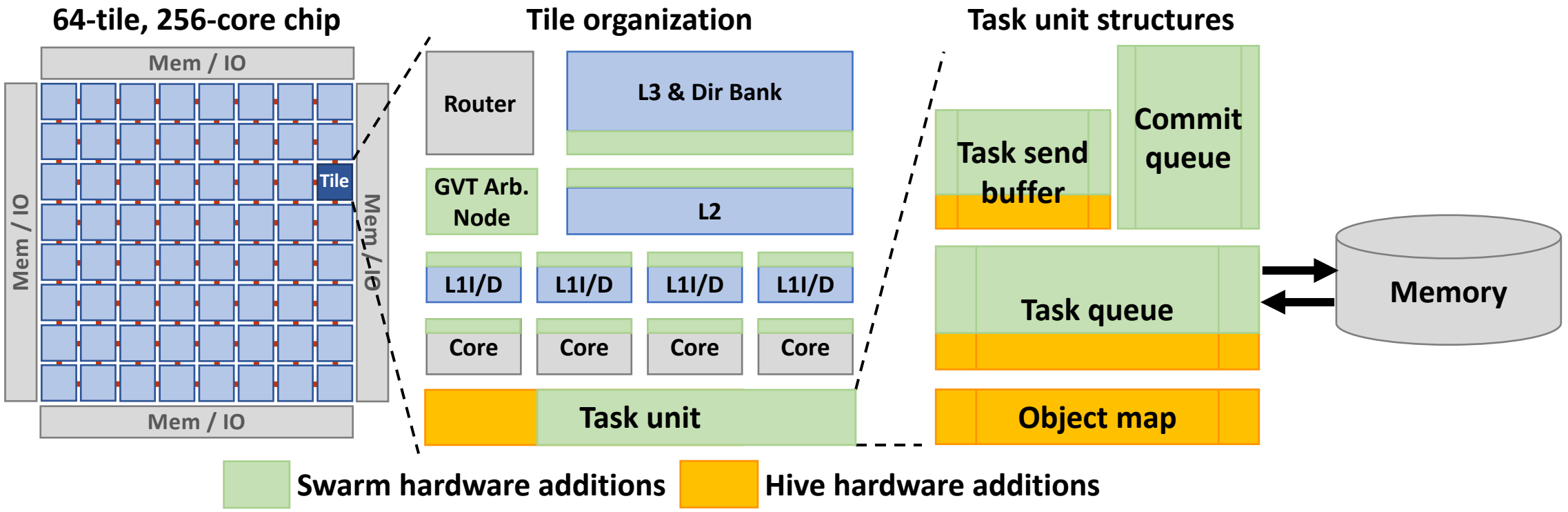
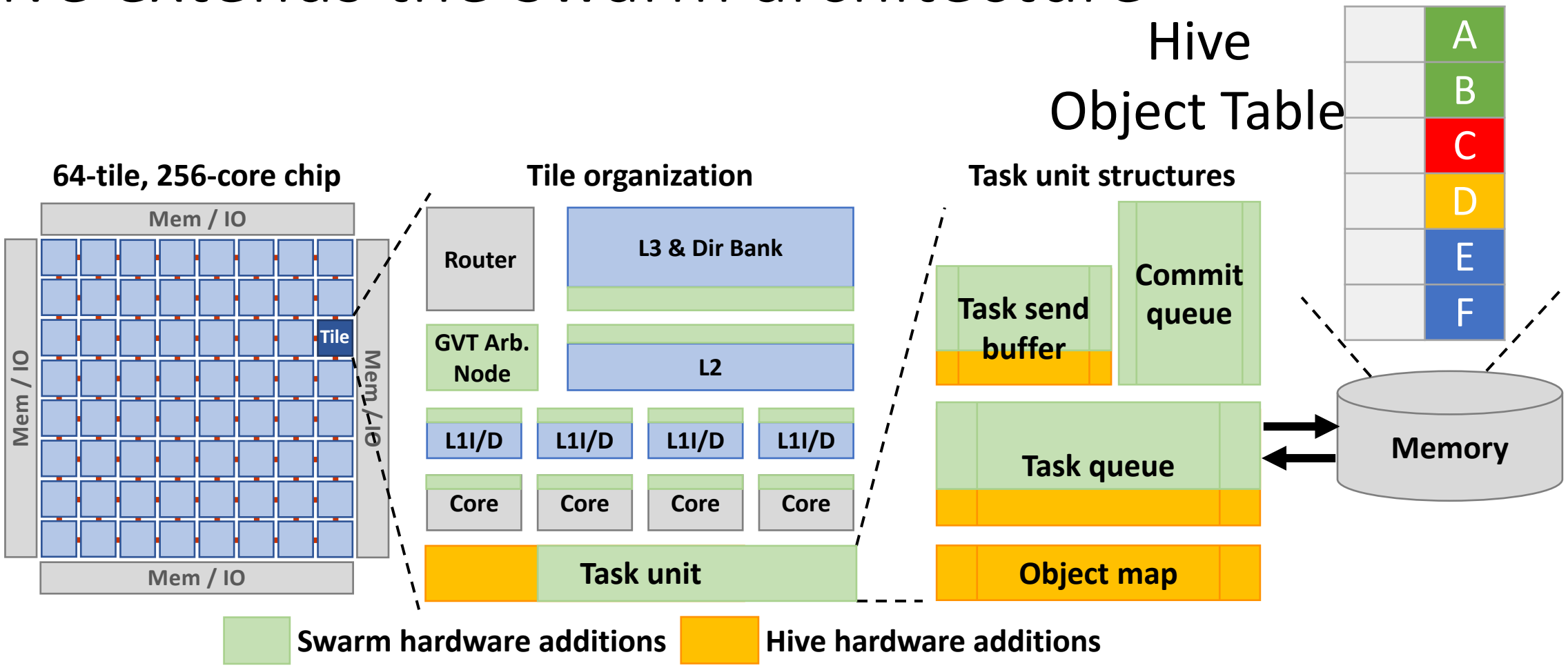
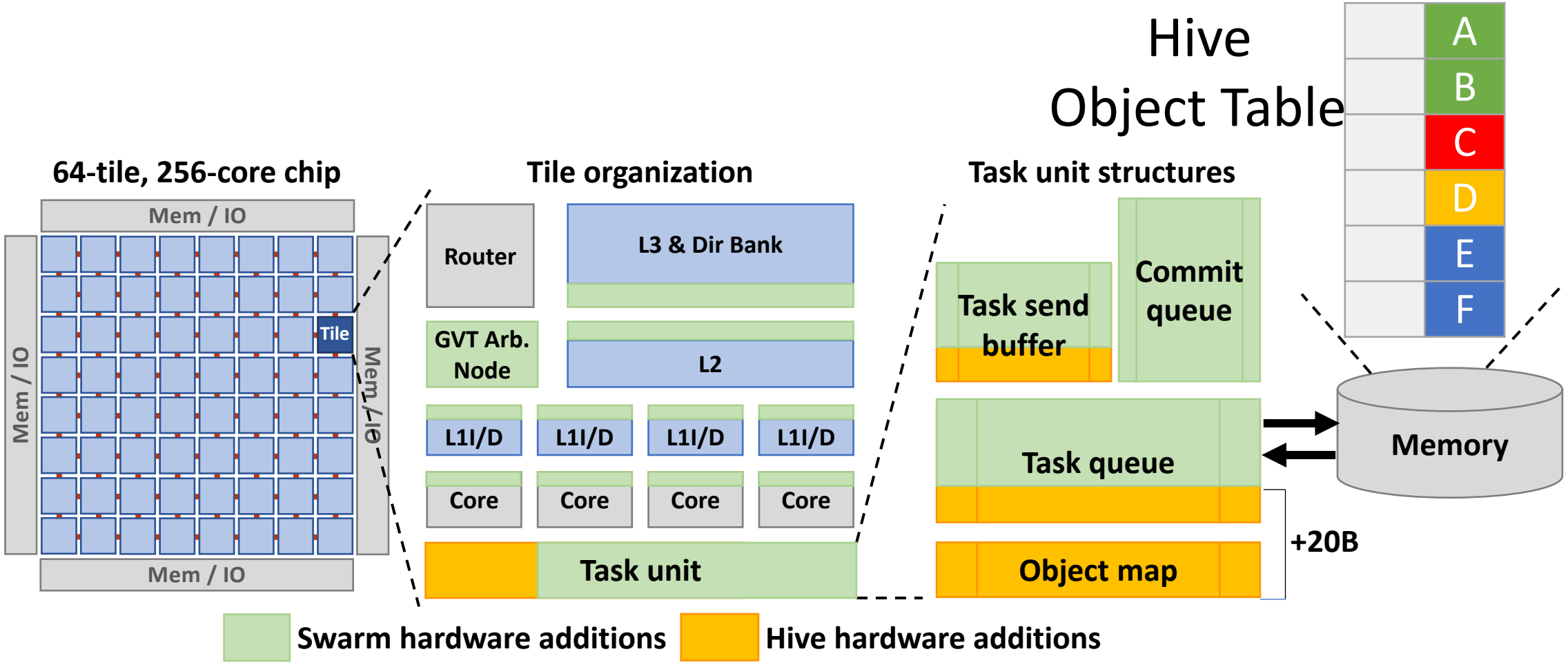


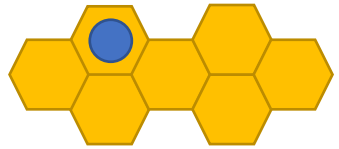
Hive extends the Swarm architecture



Hive extends the Swarm architecture



9% Task Unit Area Increase
3% Area of a Nehalem Processor

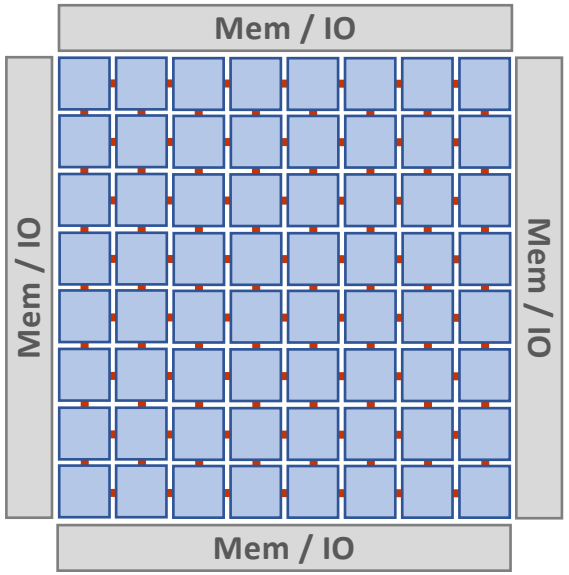


Evaluation

Methodology

Event-driven, Pin-based Simulator[1]

64 Tiles, 256 Cores



32kB L1 per core
1MB L2 per tile
256MB LLC
4 In-order, single-issue scoreboarded cores/tile
64 Task Queue entries/core
16 Commit Queue entries/core

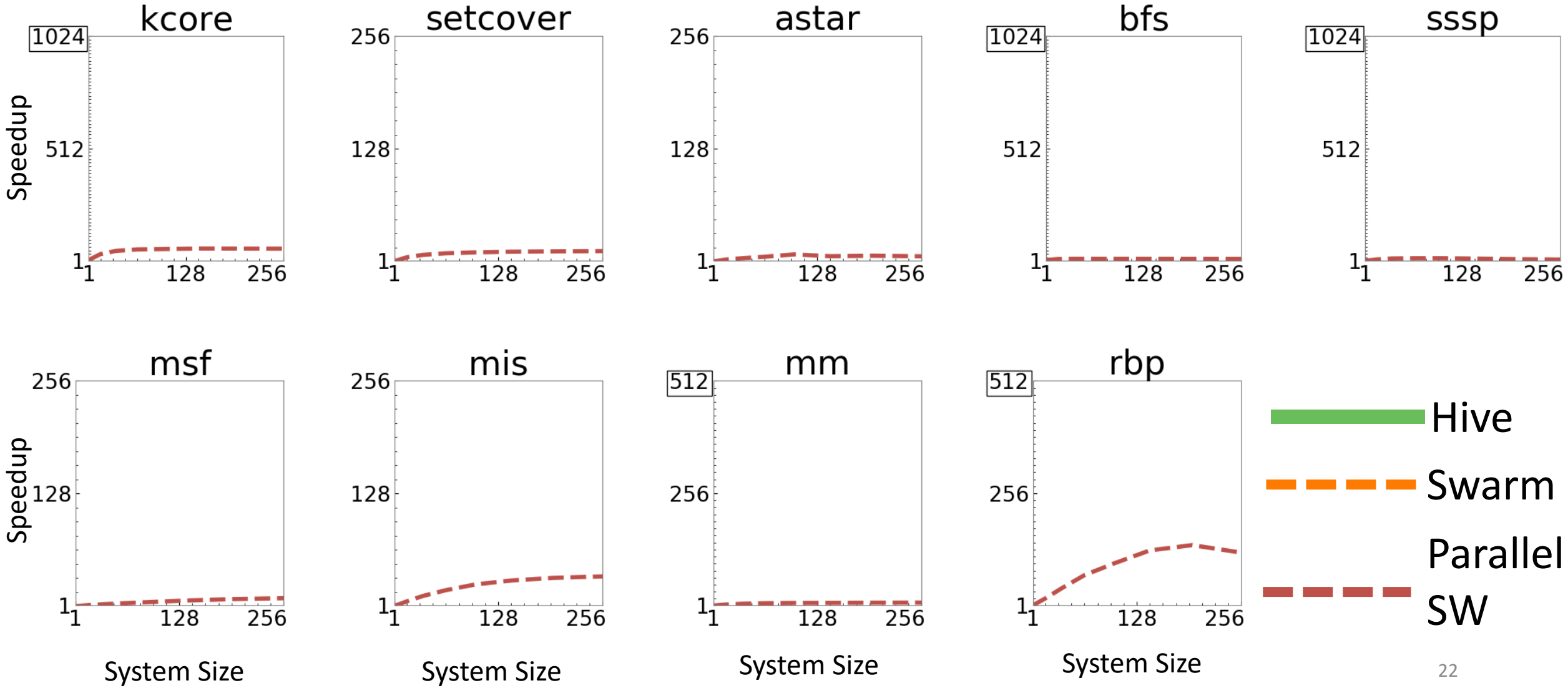
Scalability experiments up to 256 cores

- Smaller systems have fewer tiles

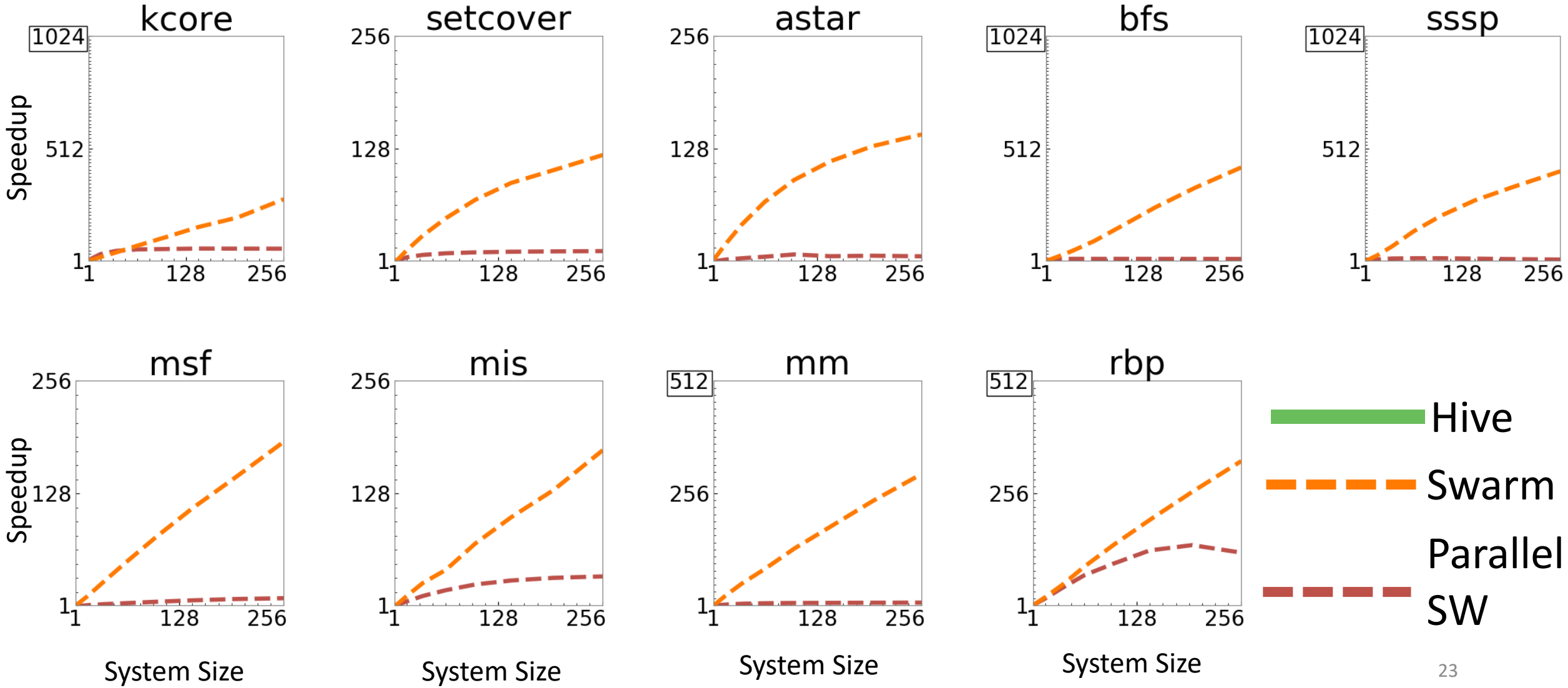
9 applications: KCore, Setcover, astar, BFS, SSSP, MSF, MIS, MM, RBP

1: https://github.com/SwarmArch/sim

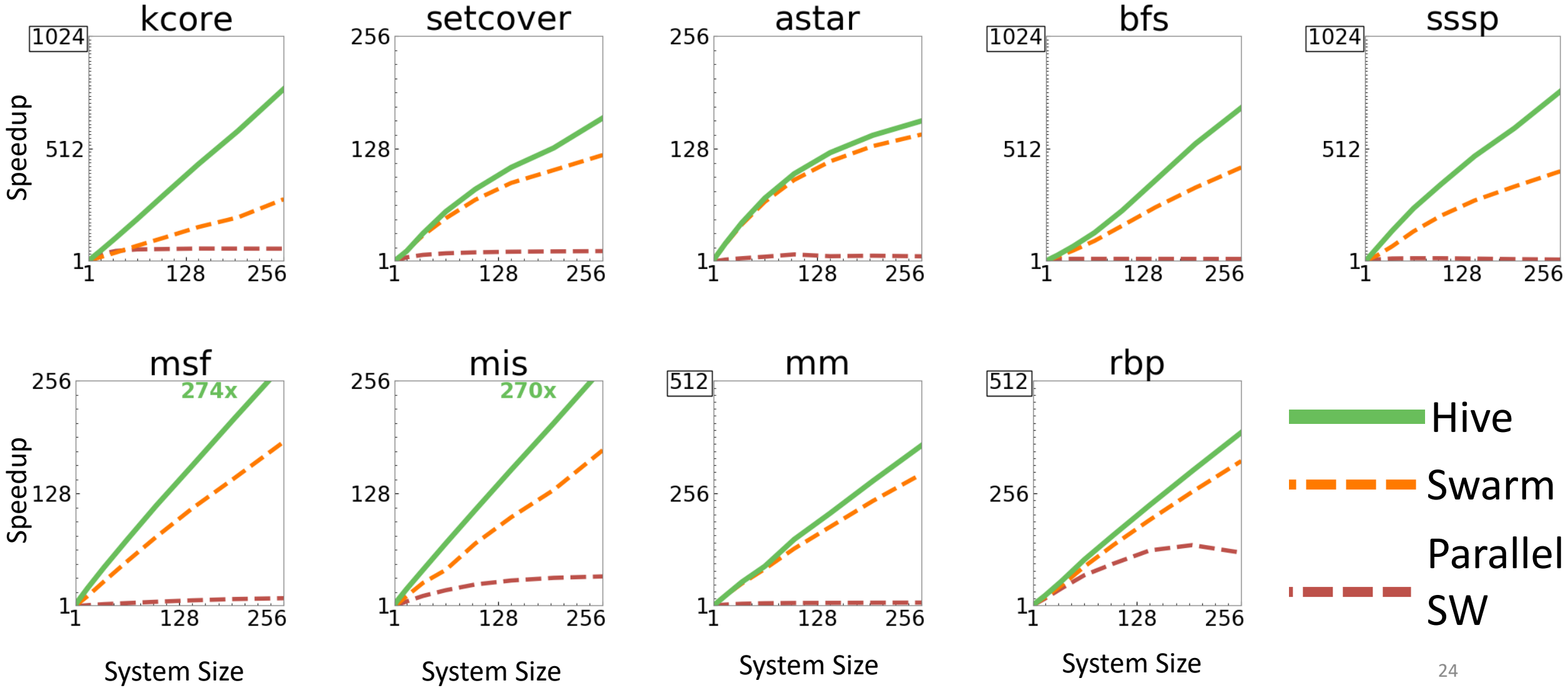
Software struggles to scale beyond 100c



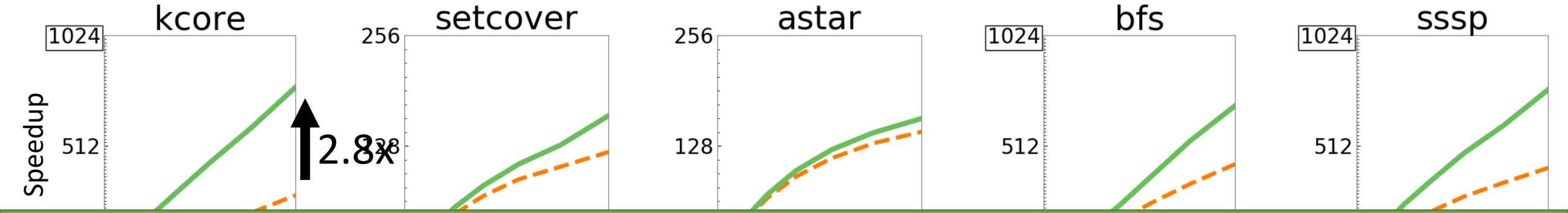
Swarm scales well sometimes



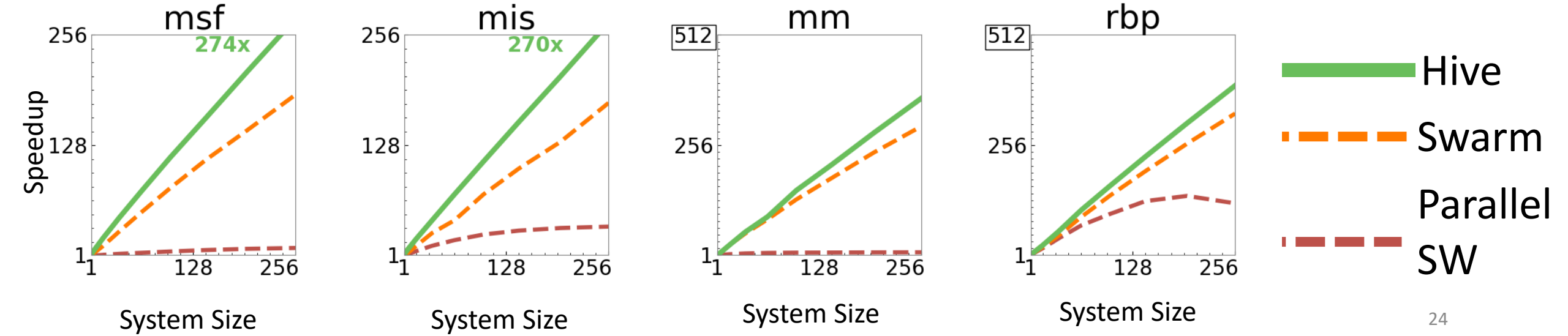
Hive is faster than Swarm



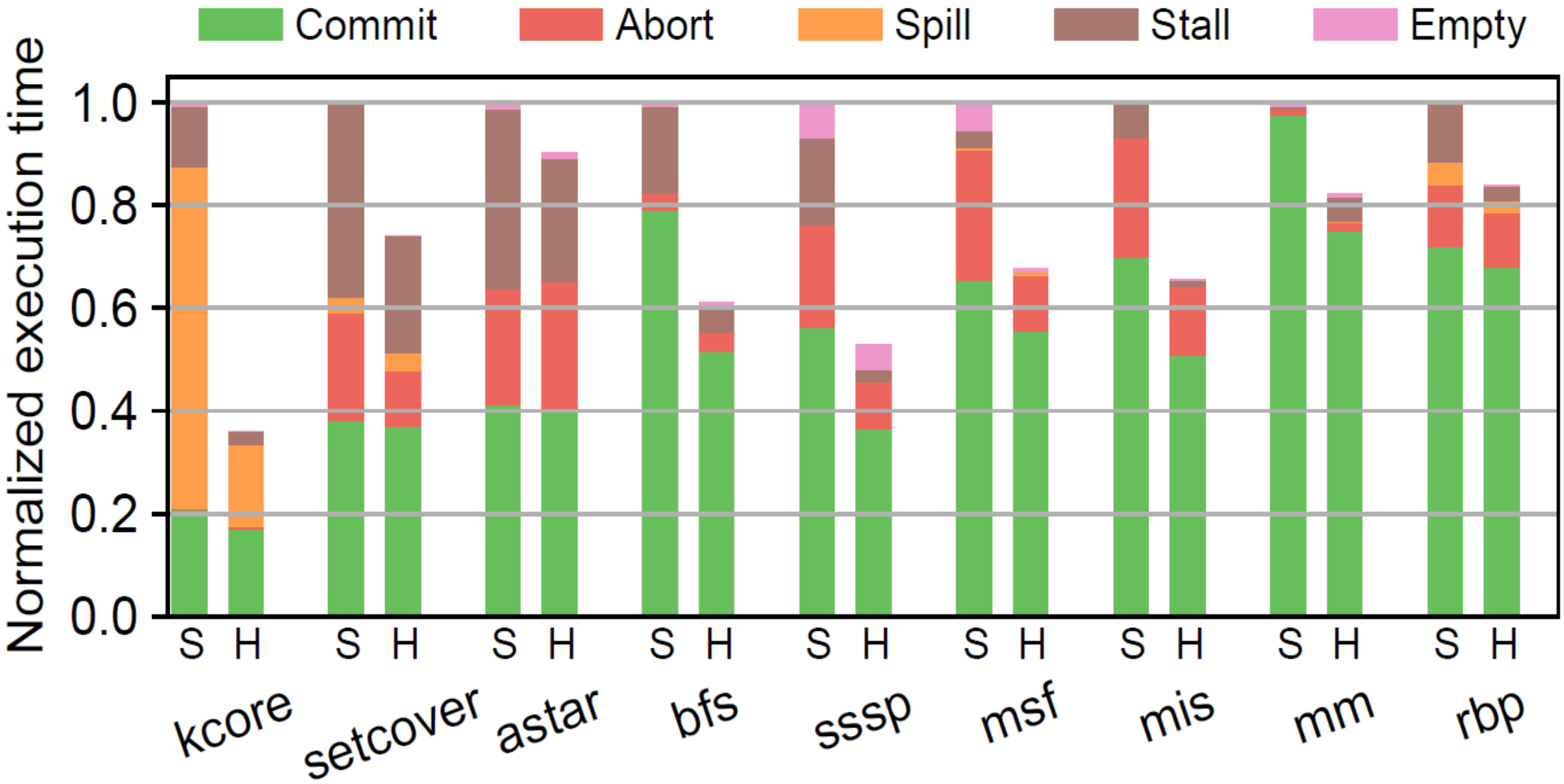
Hive is faster than Swarm



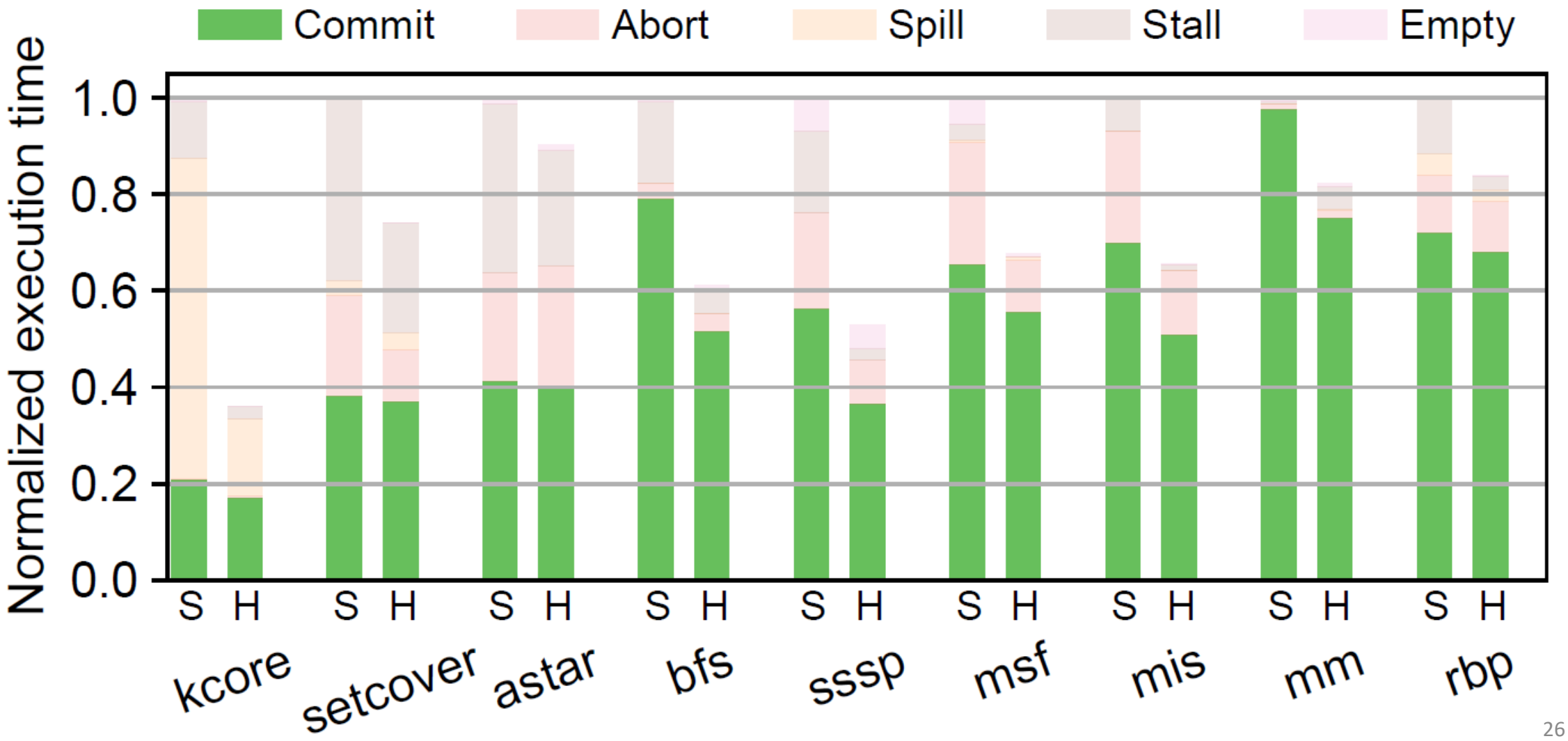
Hive is up to 2.8x faster than Swarm



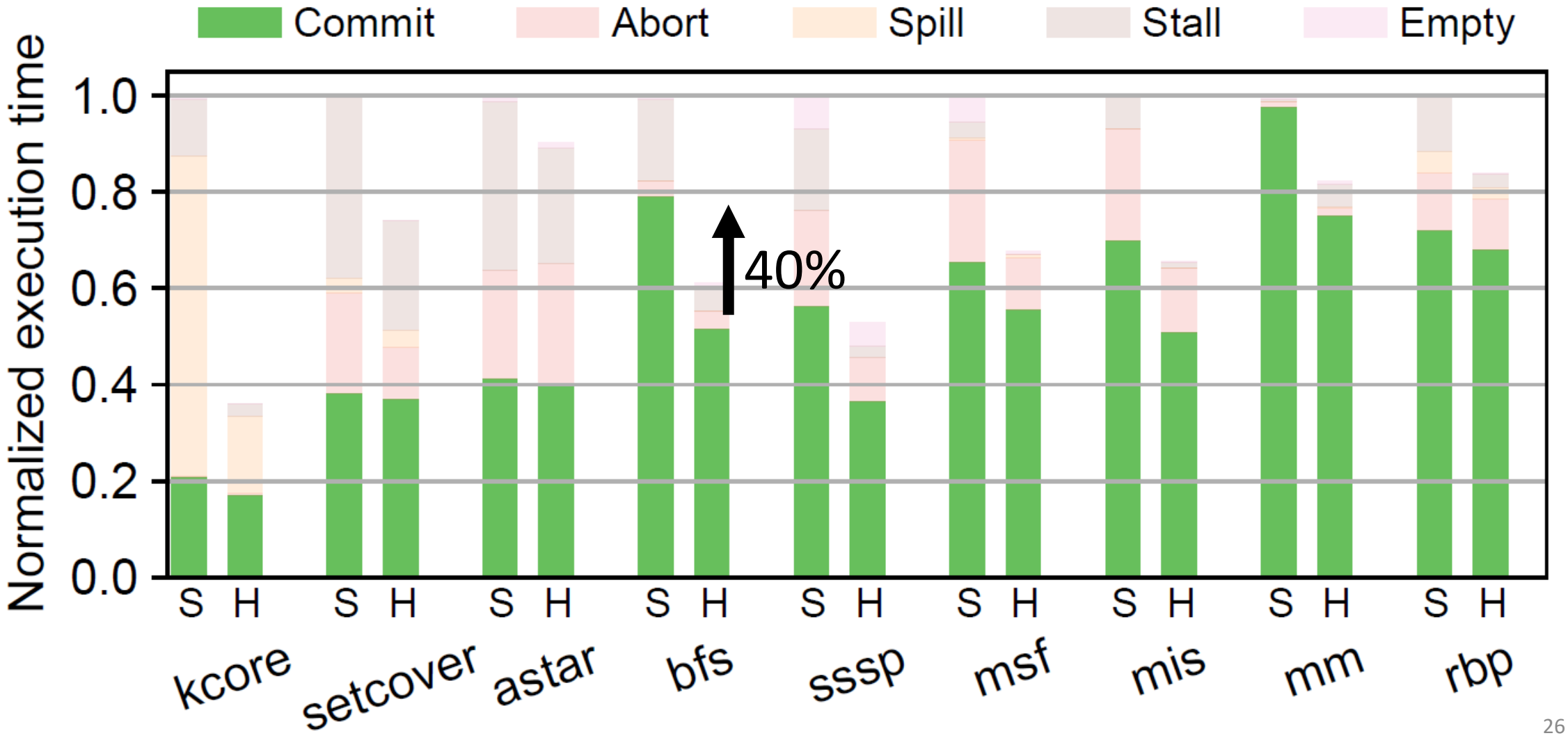
Breaking down Hive vs. Swarm at 256 cores



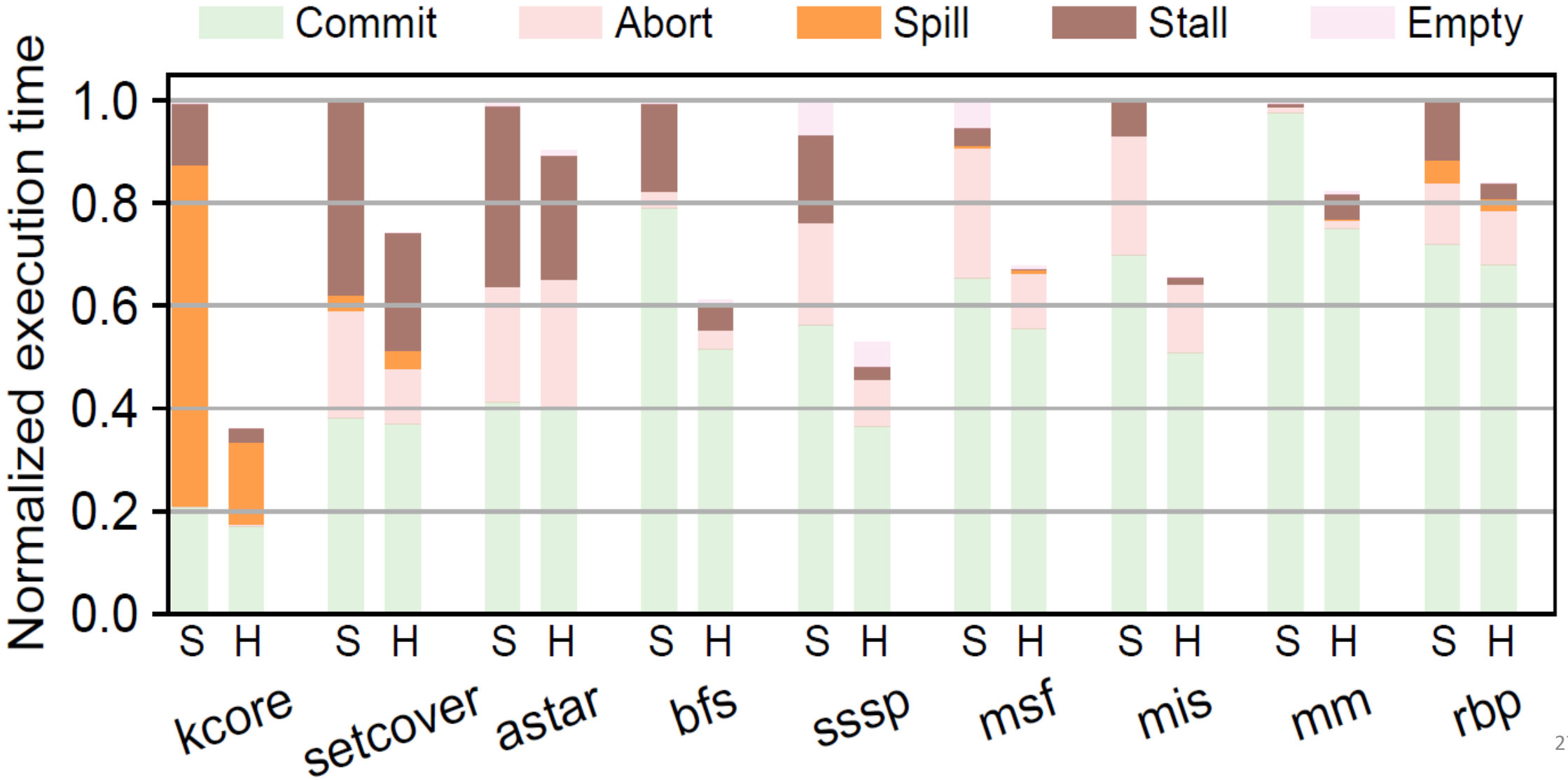
Hive does less work

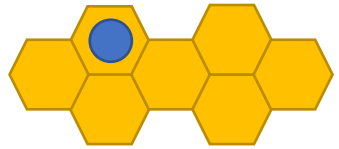


Hive does less work



Hive reduces queue pressure





Conclusions and Q+A

- Priority updates are useful operations for ordered algorithms
- The scheduler dependences created by these updates require task versioning and mootness detection for speculation
- Hive extracts parallelism by speculating on data, control, and scheduler dependences

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ISCA 2022

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