A Scalable Architecture for Ordered Parallelism

Mark Jeffrey, Suvinay Subramanian, Cong Yan, Joel Emer, Daniel Sanchez

MICRO 2015

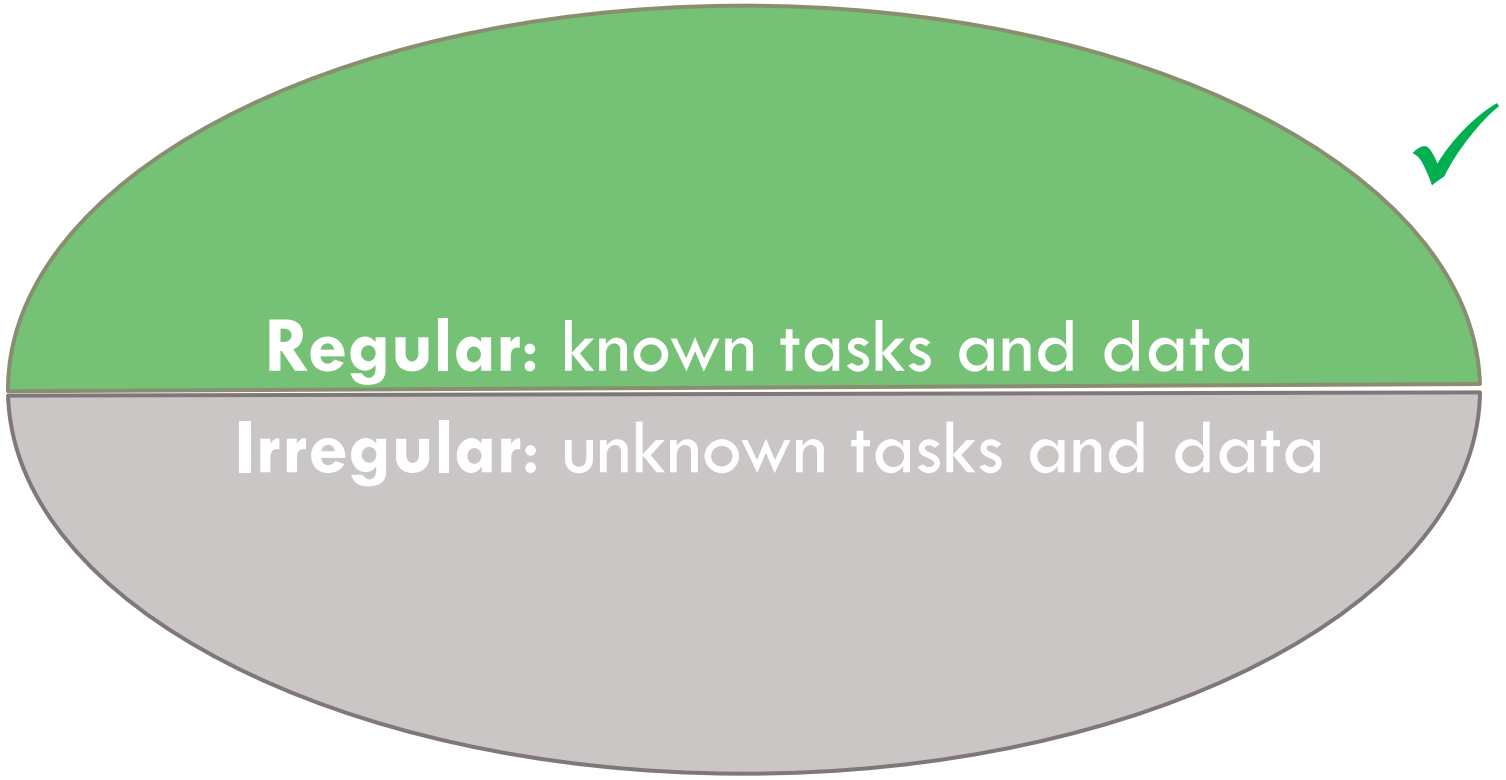
Massachusetts Institute of Technology

Multicores Target Easy Parallelism

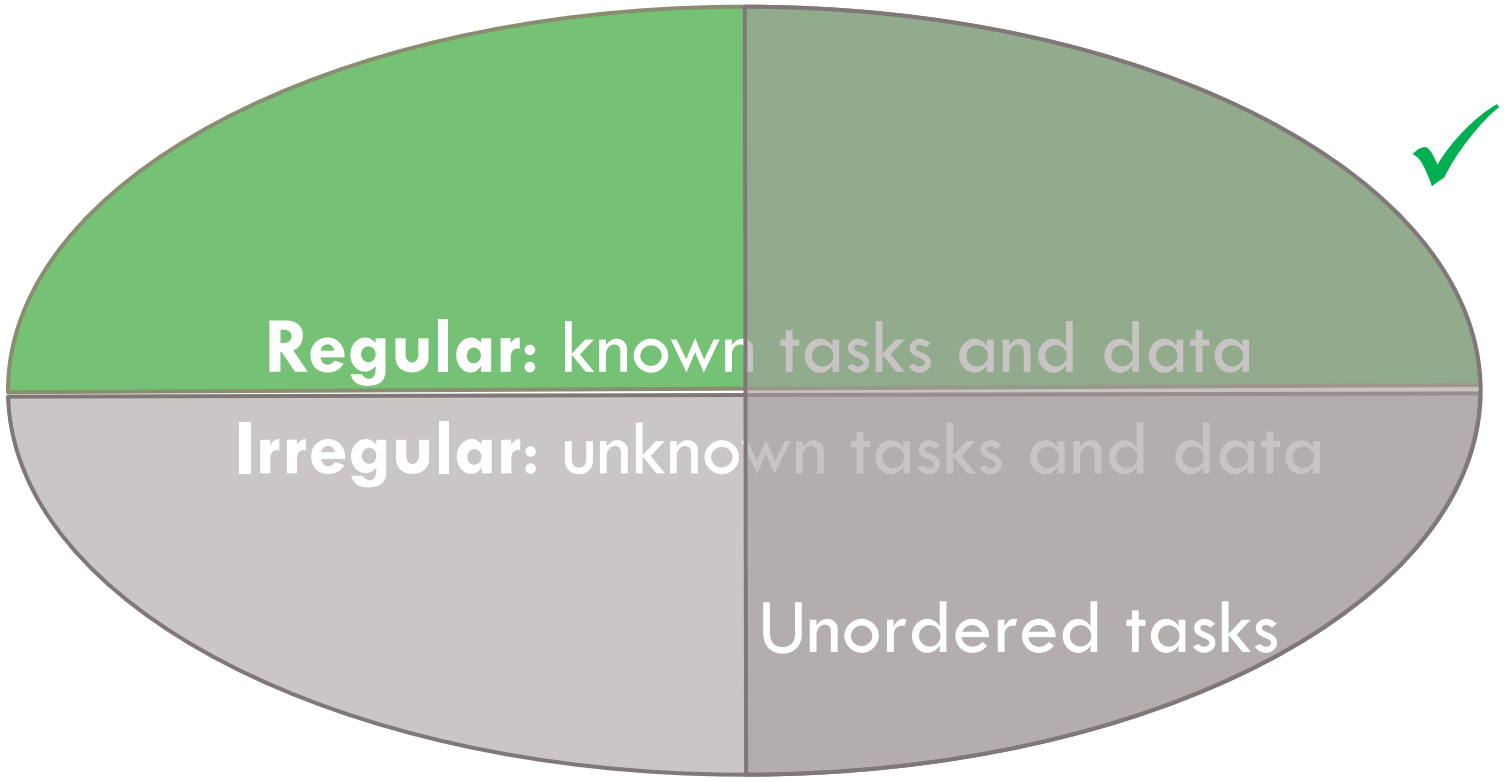
Multicores Target Easy Parallelism

Multicores Target Easy Parallelism

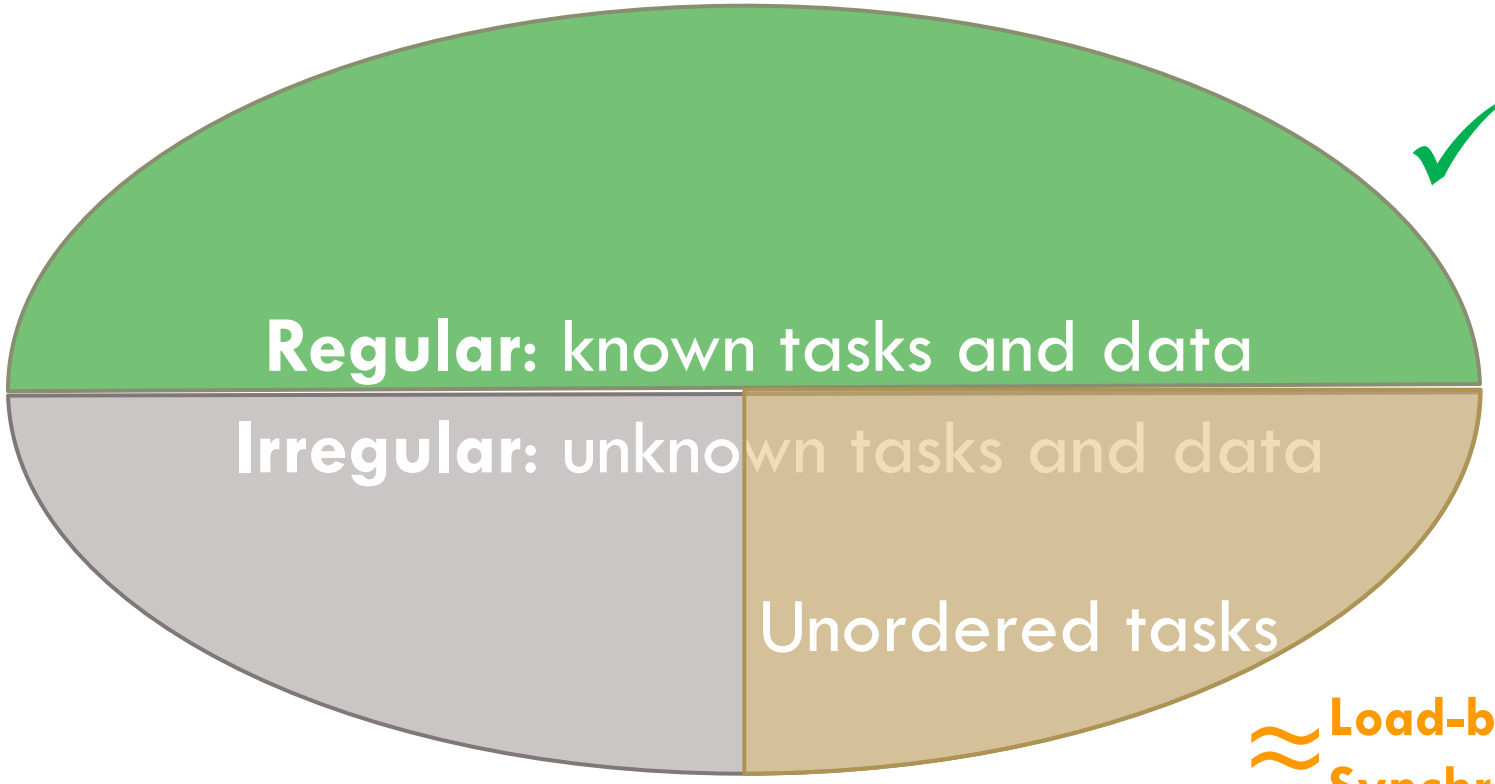
Multicores Target Easy Parallelism



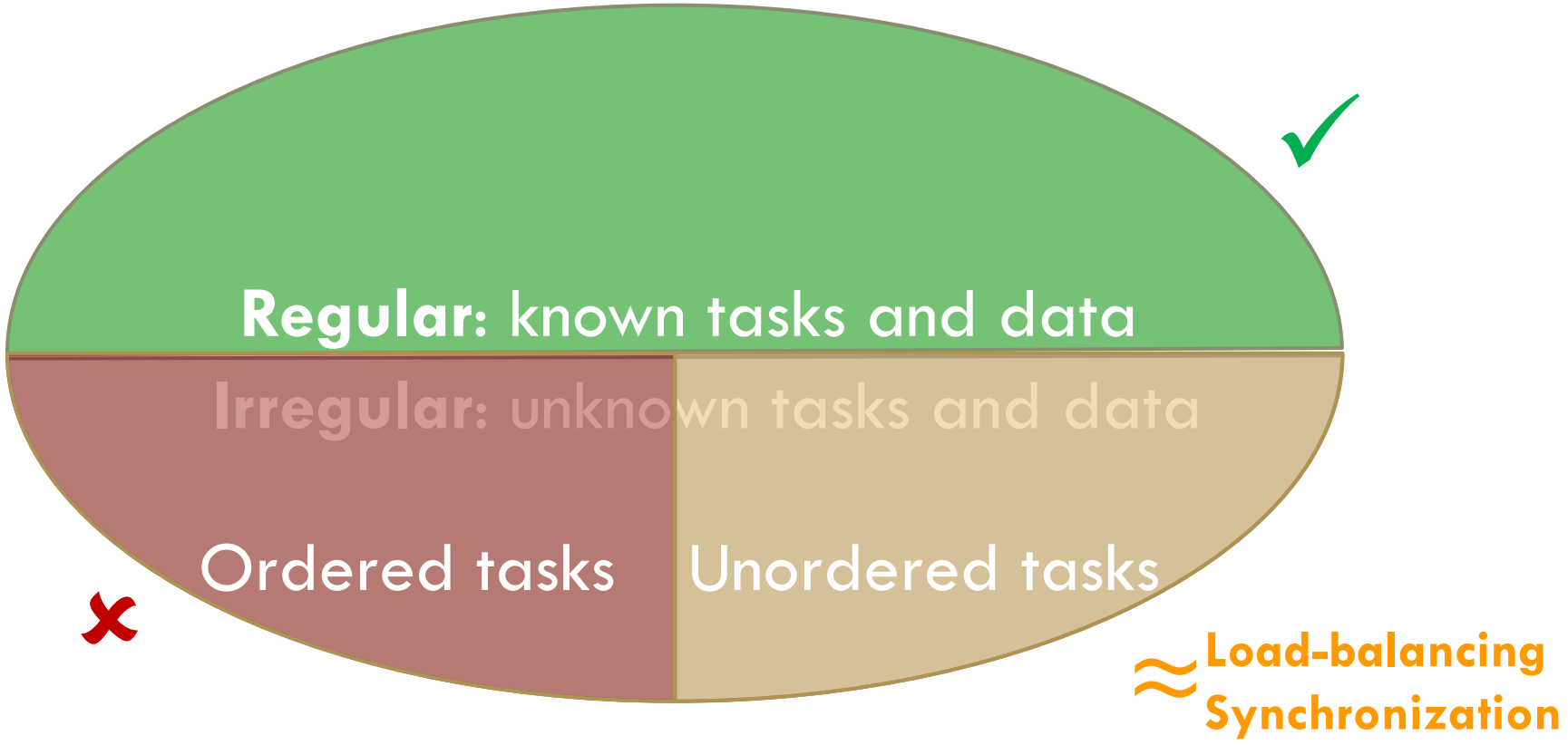
Multicores Target Easy Parallelism



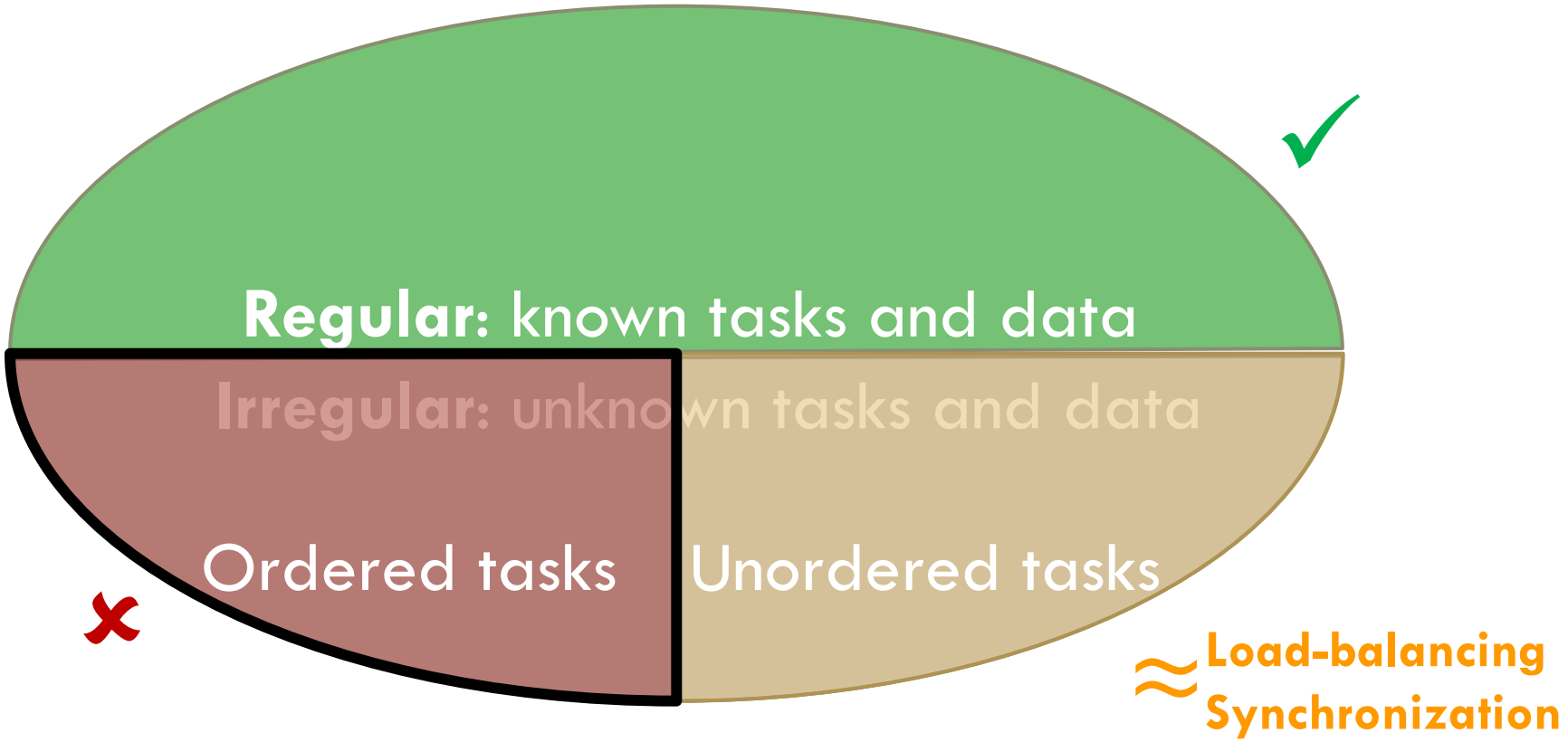
Multicores Target Easy Parallelism



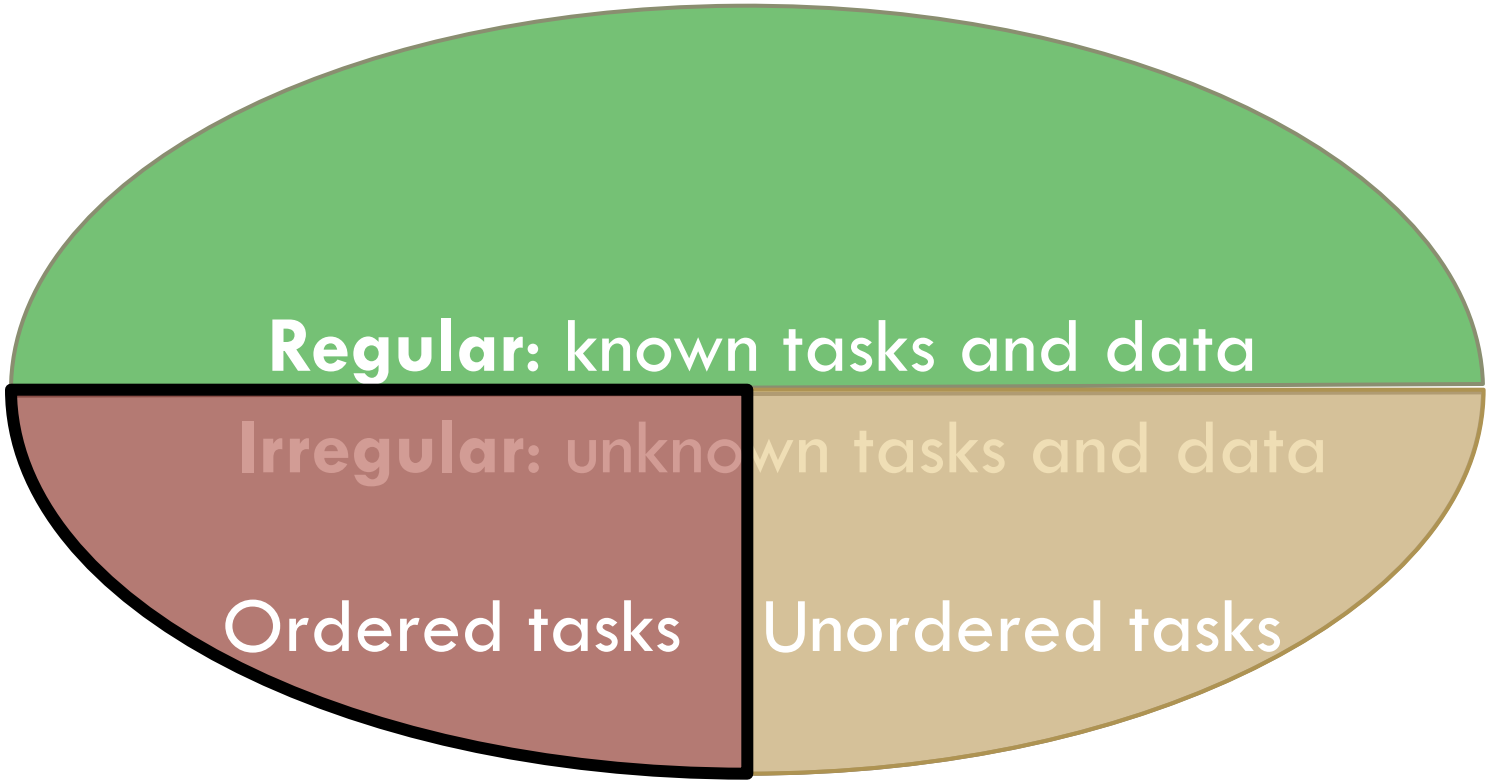
Multicores Target Easy Parallelism



Multicores Target Easy Parallelism

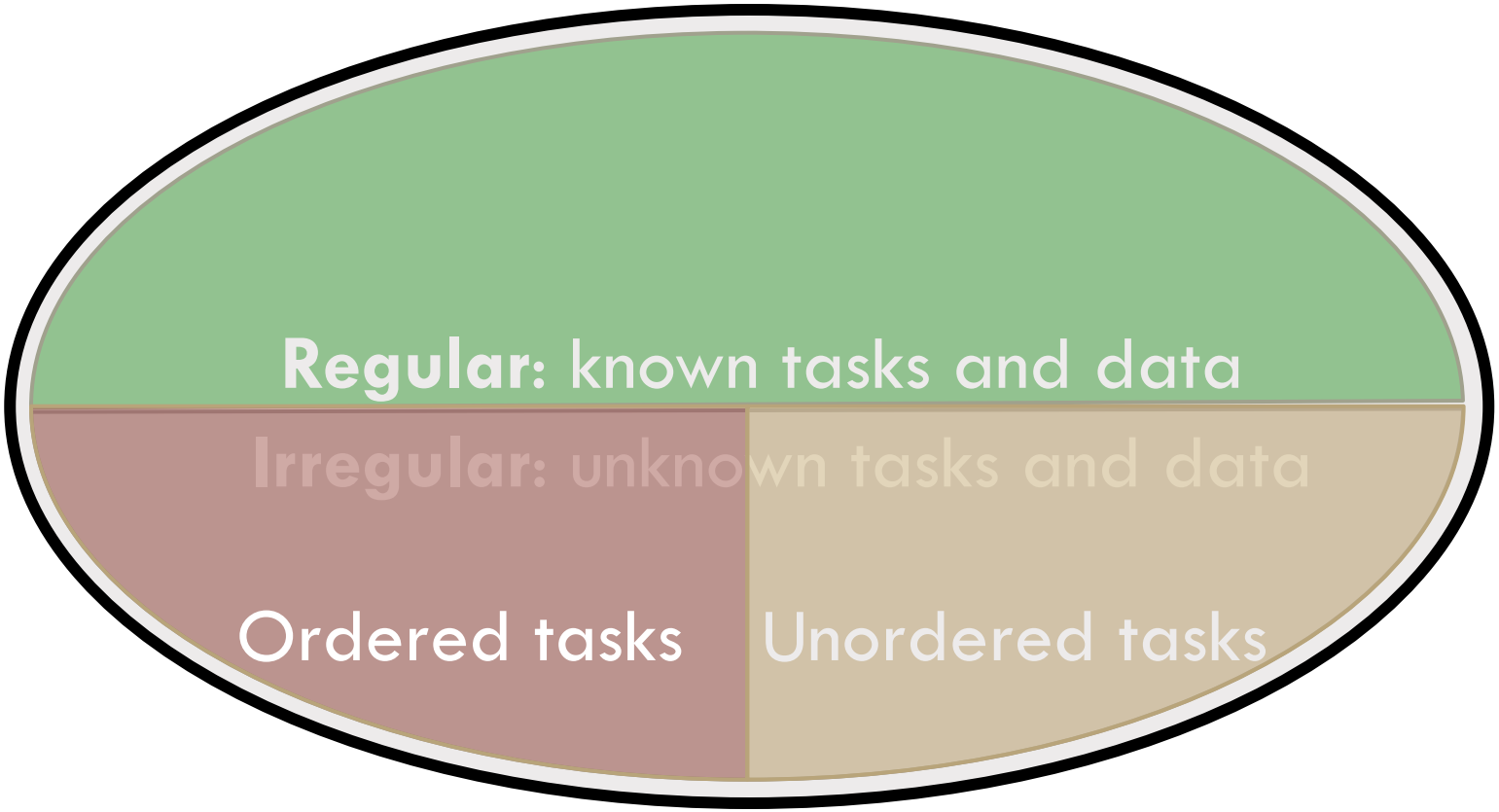


Multicores Target Easy Parallelism



Ordering is a simple and general form of synchronization

Multicores Target Easy Parallelism



Ordering is a simple and general form of synchronization

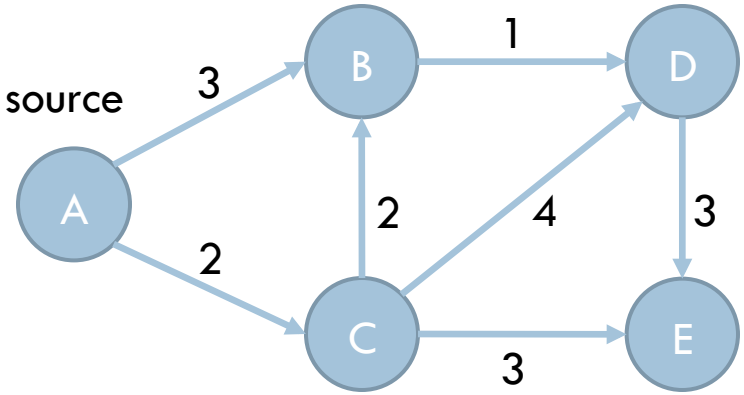
Support for **order** enables widespread parallelism

Outline

- Understanding Ordered Parallelism
- Swarm
- Evaluation

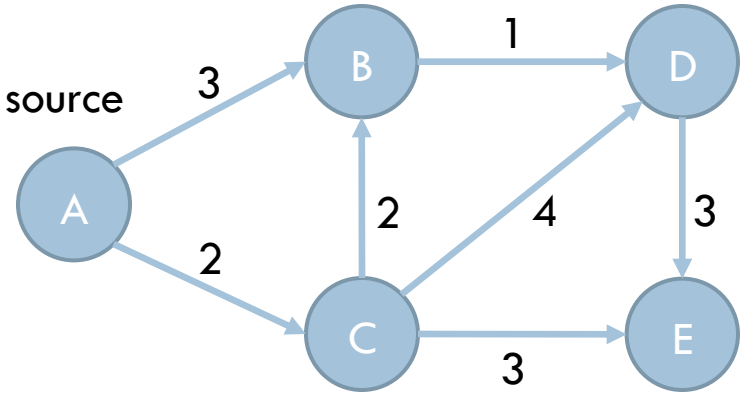
Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges

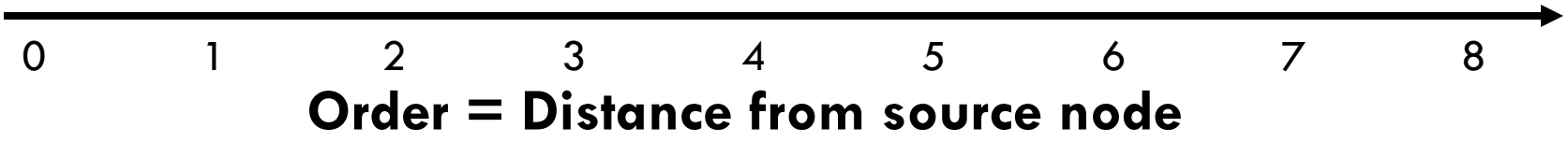


Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges



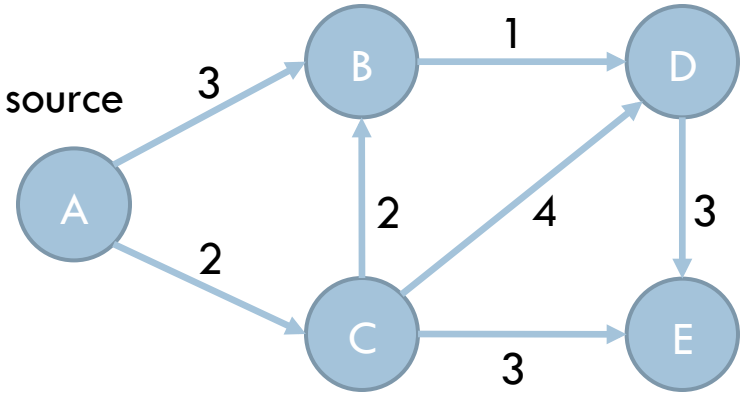
Tasks



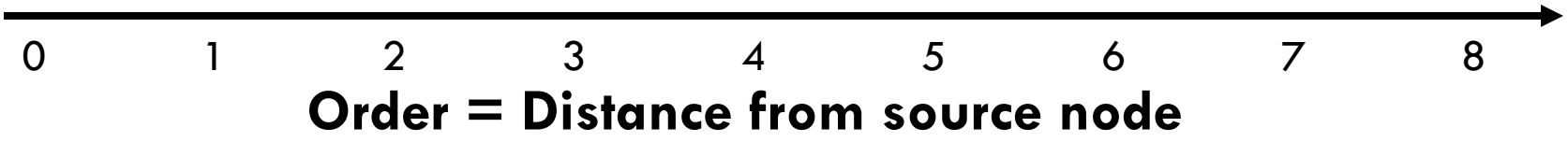
Order = Distance from source node

Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges



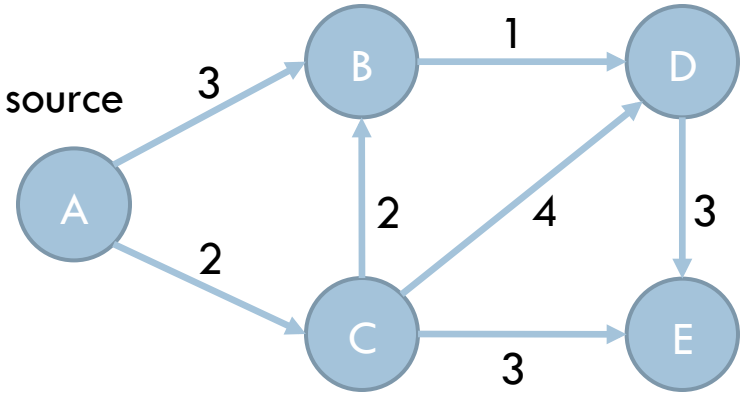
Tasks



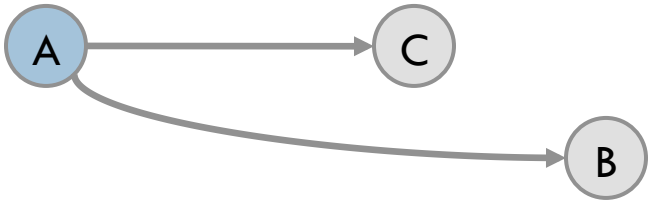
Order = Distance from source node

Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges



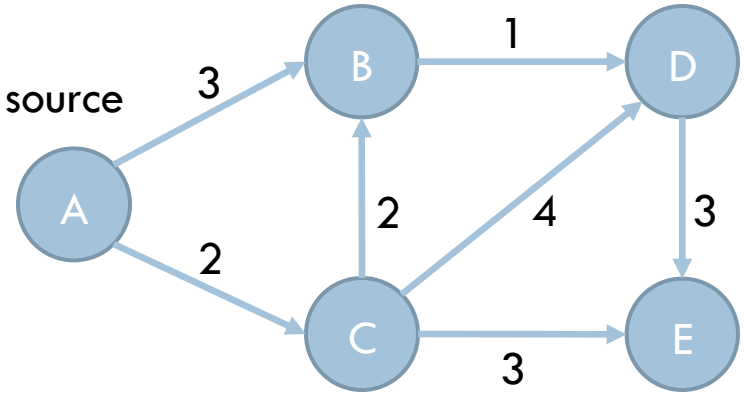
Tasks



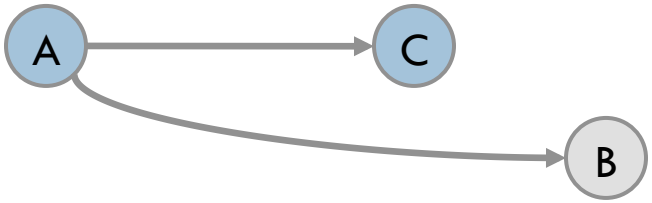
Order = Distance from source node

Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges



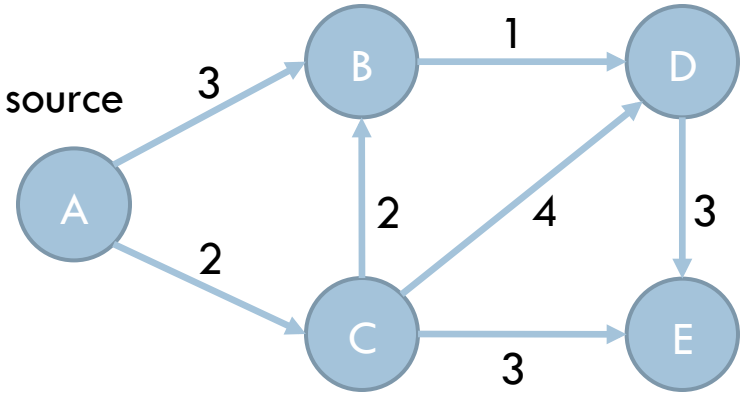
Tasks

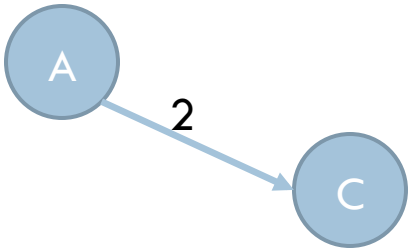


Order = Distance from source node

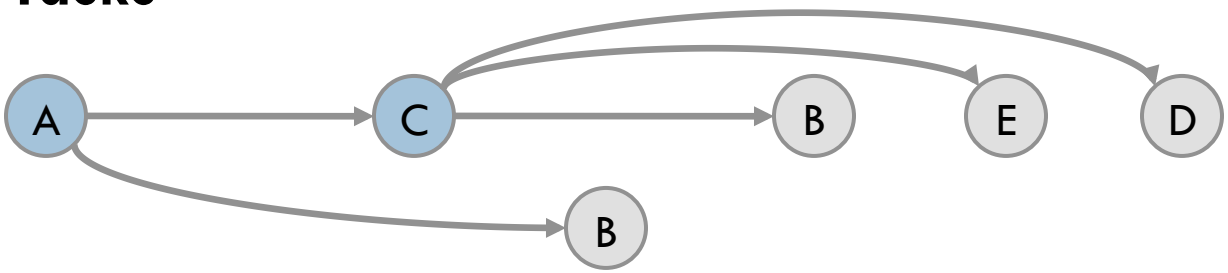
Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges





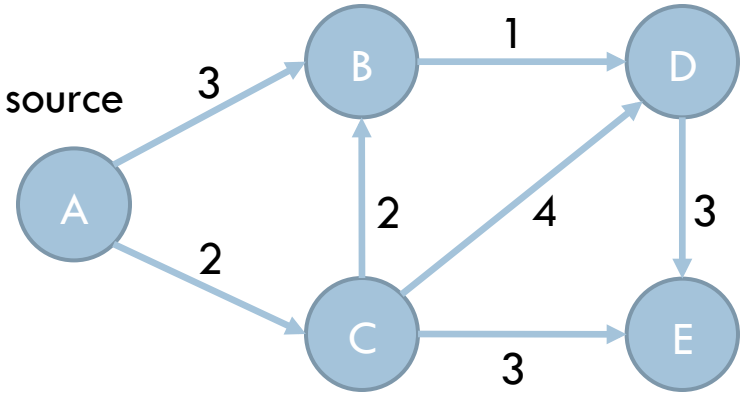
Tasks

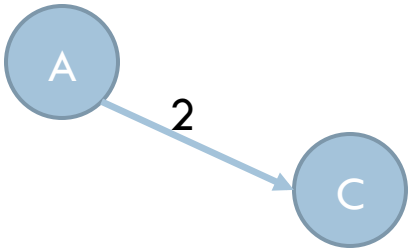


Order = Distance from source node

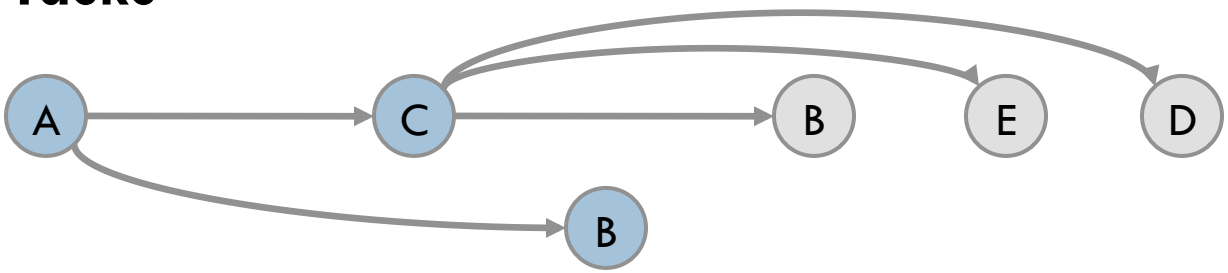
Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges





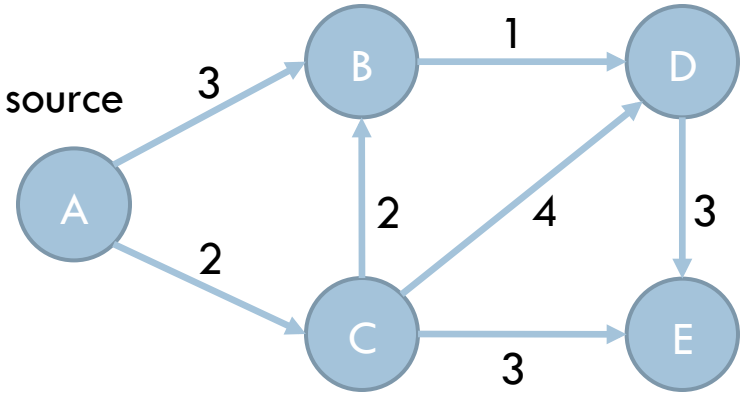
Tasks

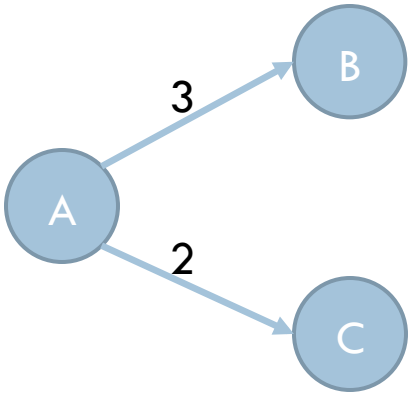


Order = Distance from source node

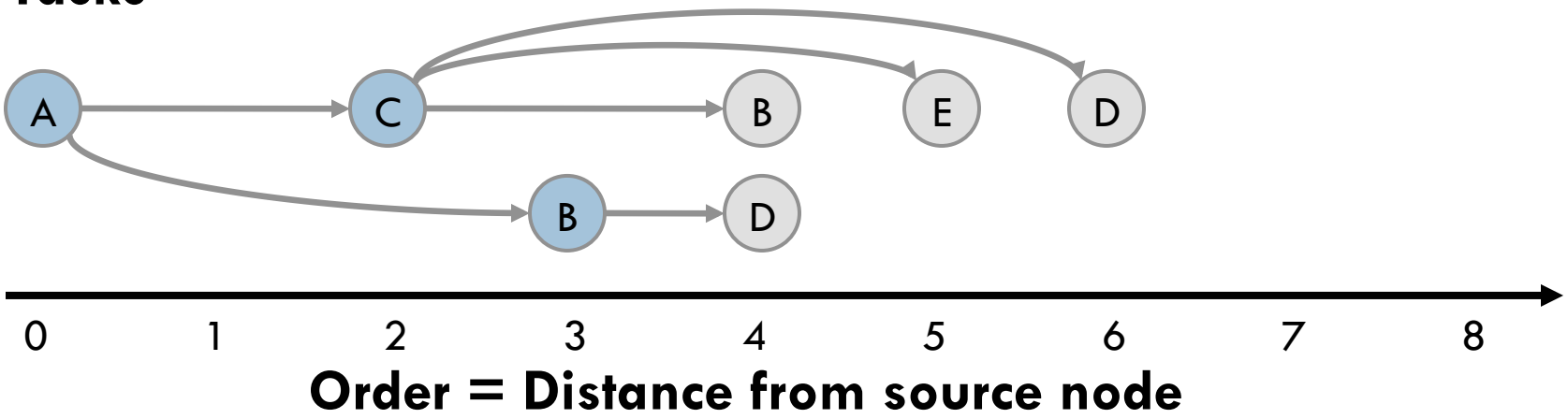
Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges



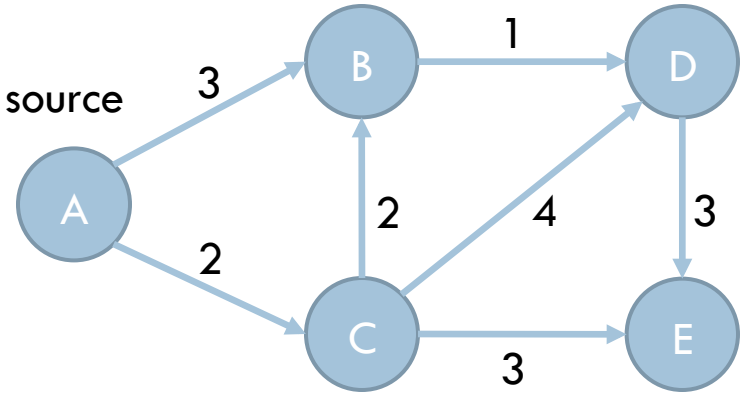


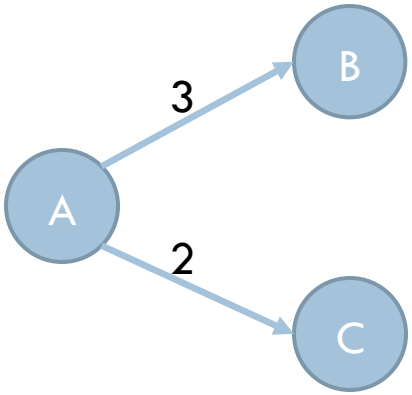
Tasks



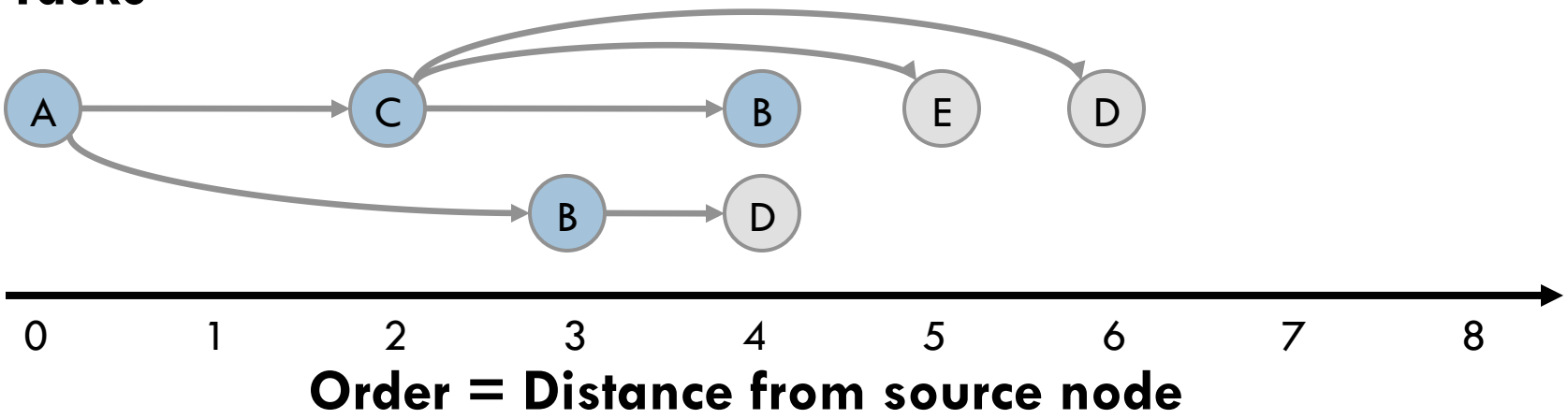
Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges



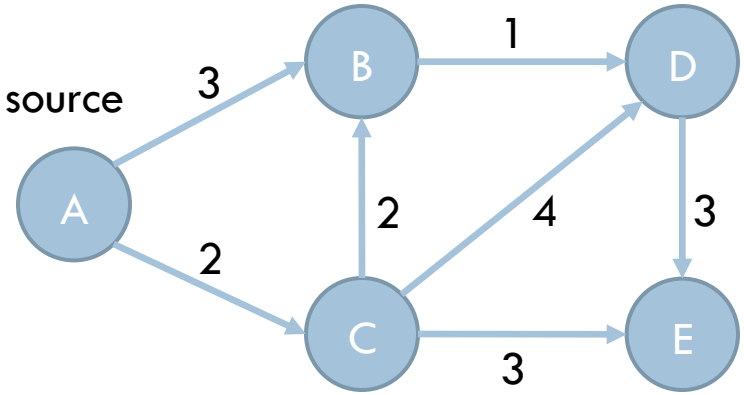


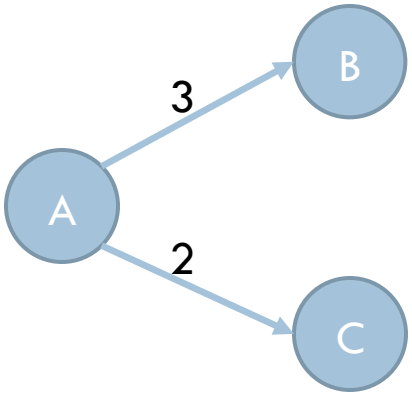
Tasks



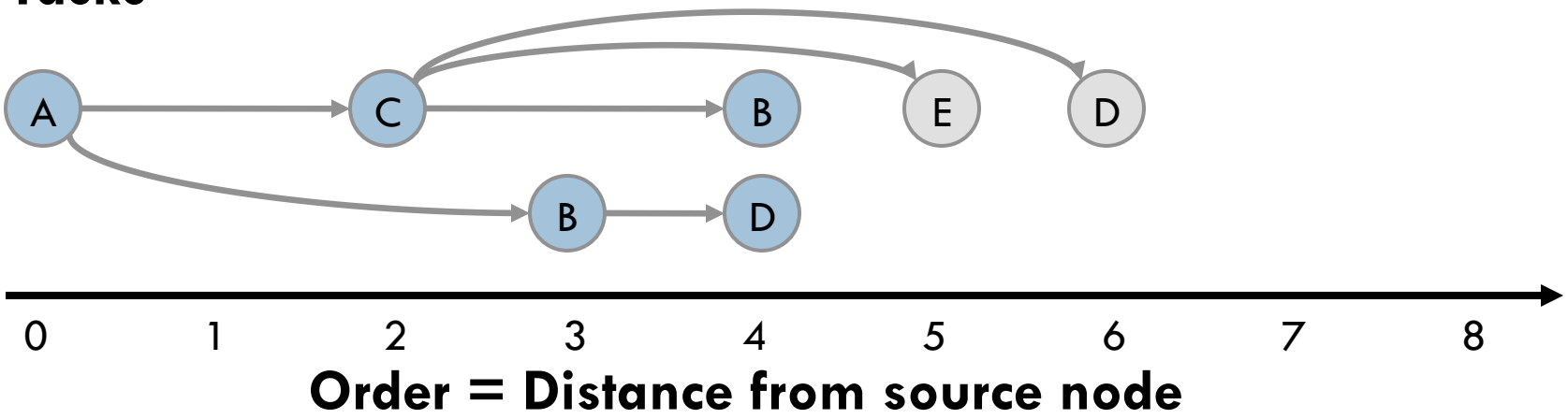
Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges



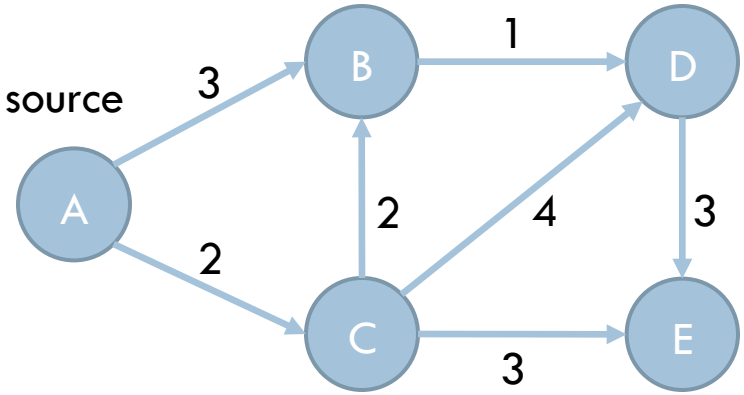


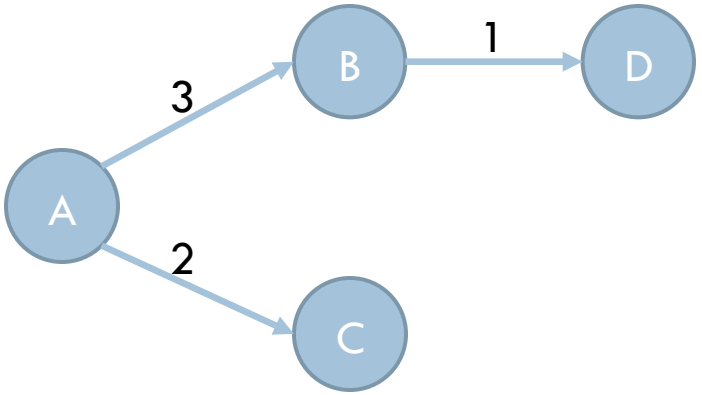
Tasks



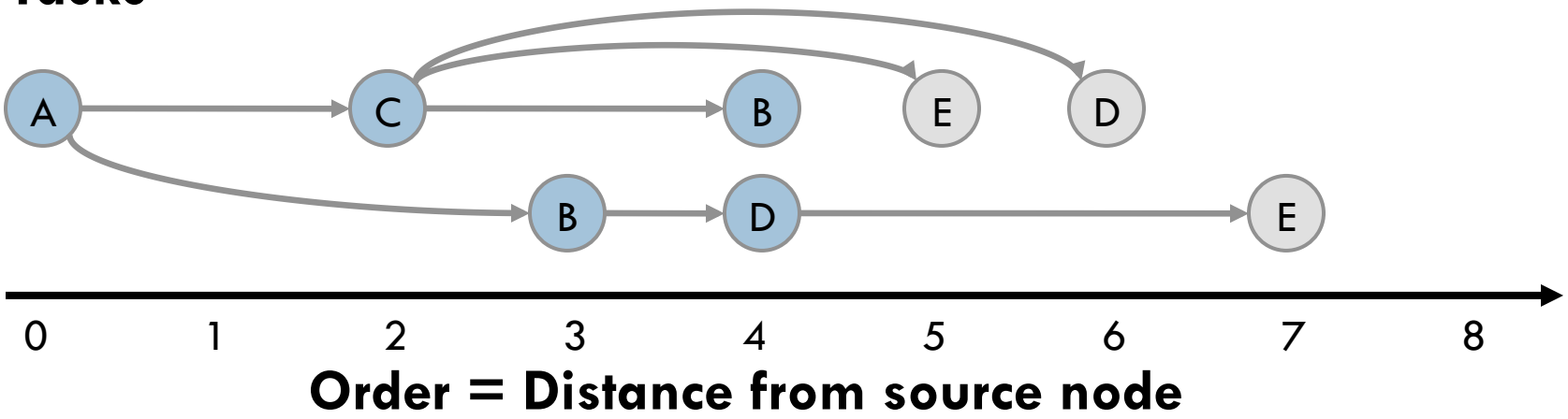
Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges





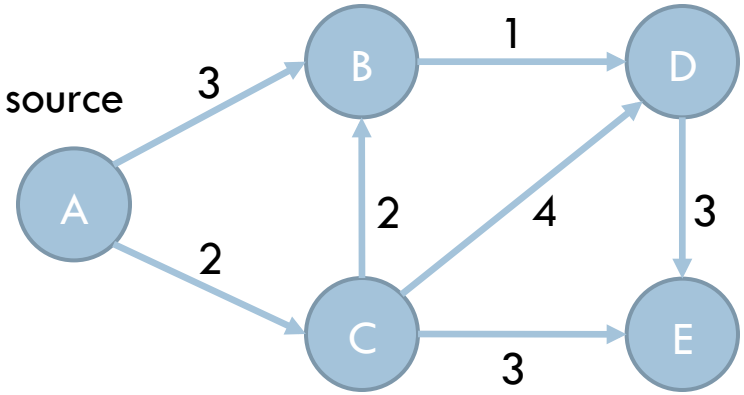
Tasks

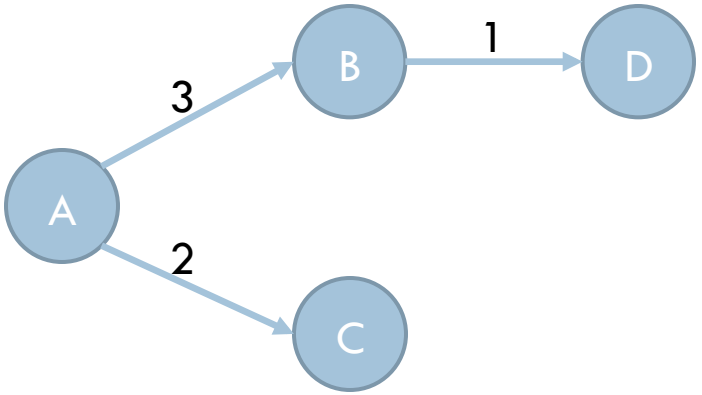


Order = Distance from source node

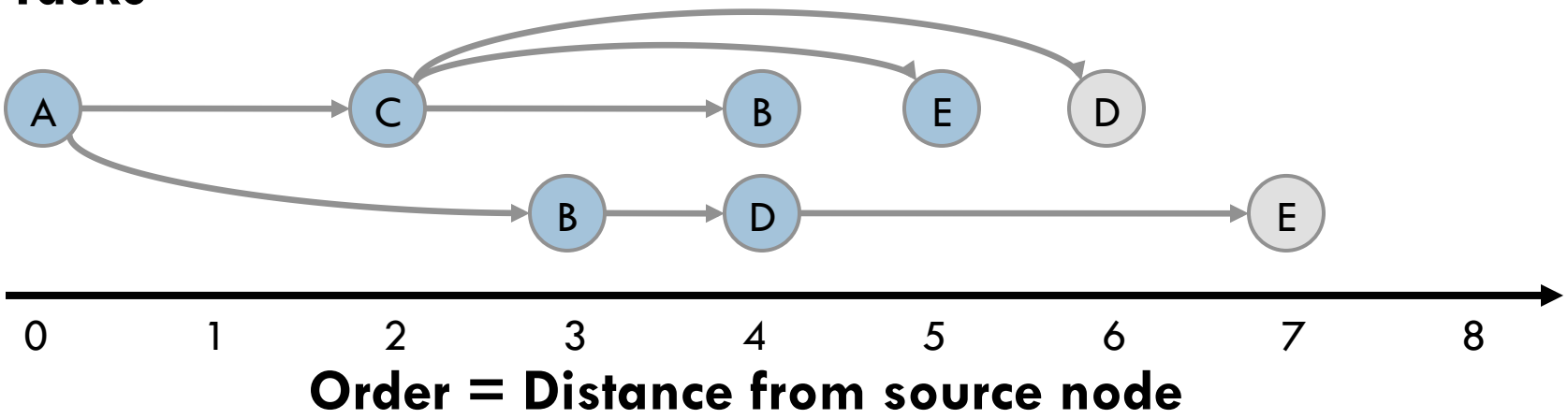
Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges





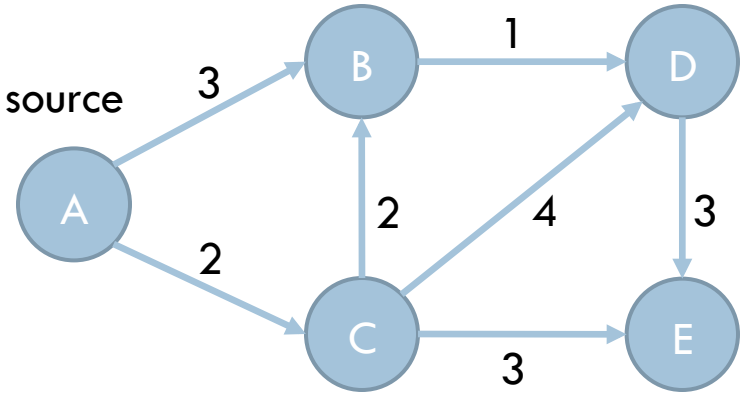
Tasks

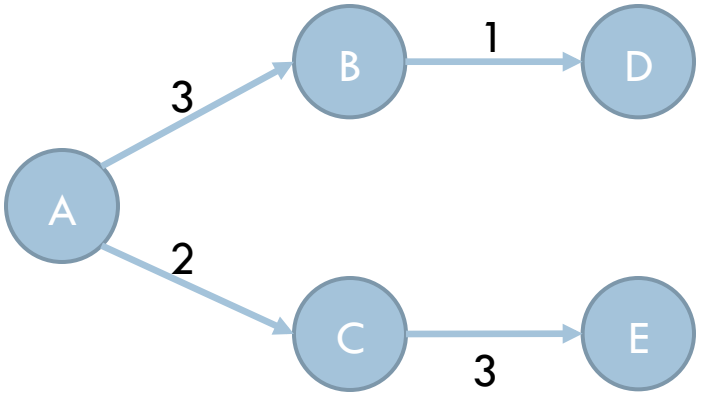


Order = Distance from source node

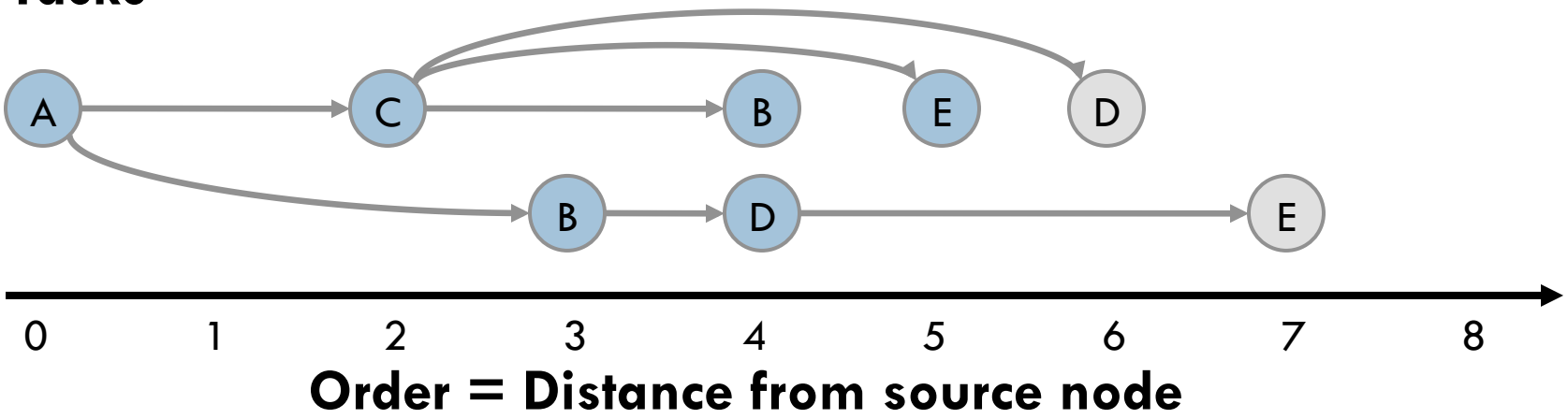
Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges





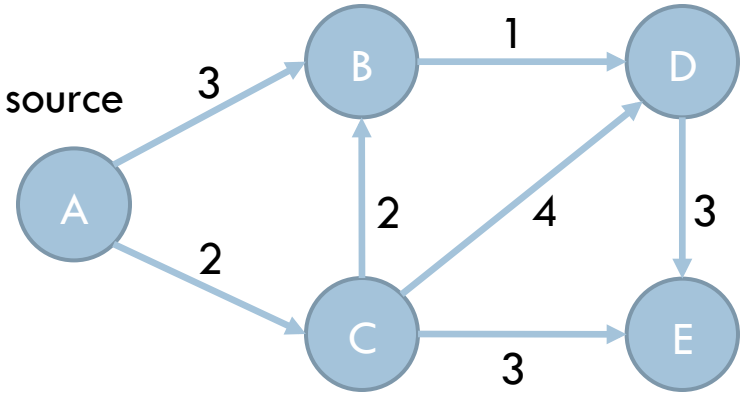
Tasks

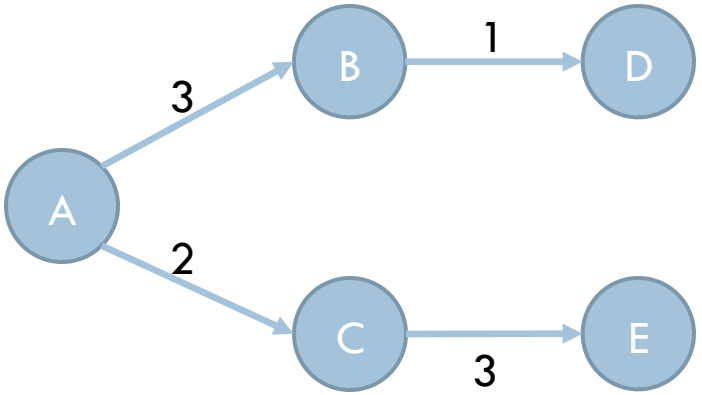


Order = Distance from source node

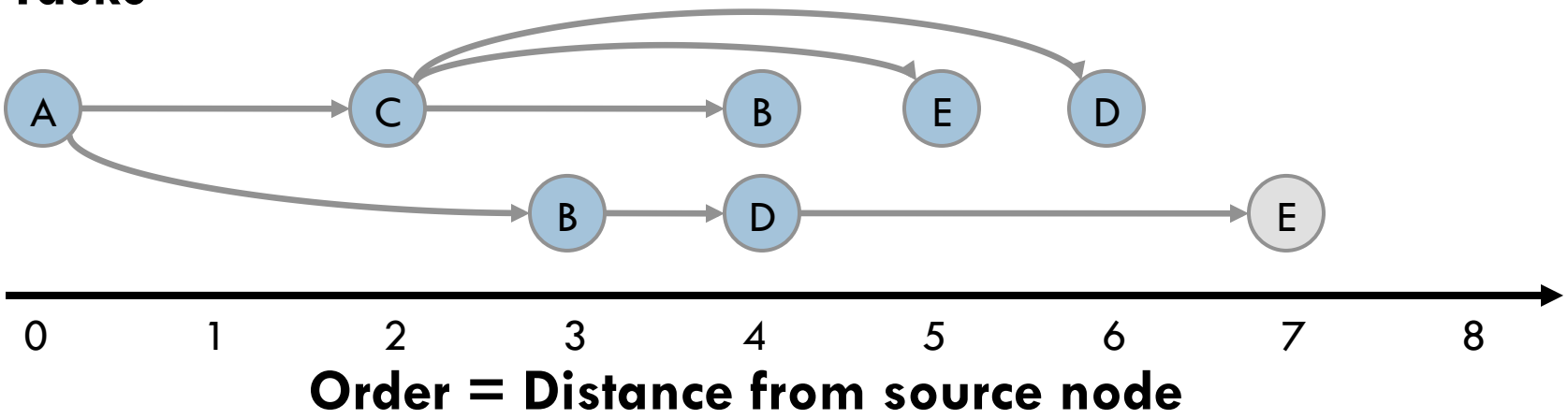
Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges





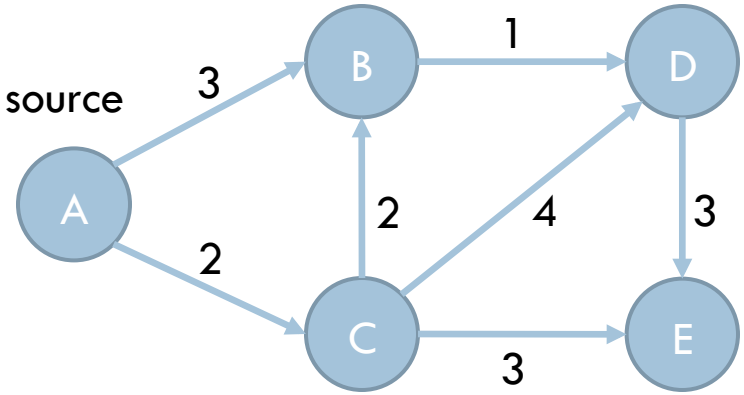
Tasks

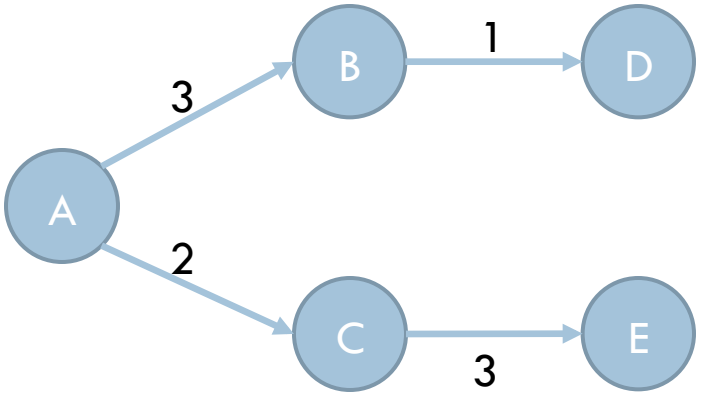


Order = Distance from source node

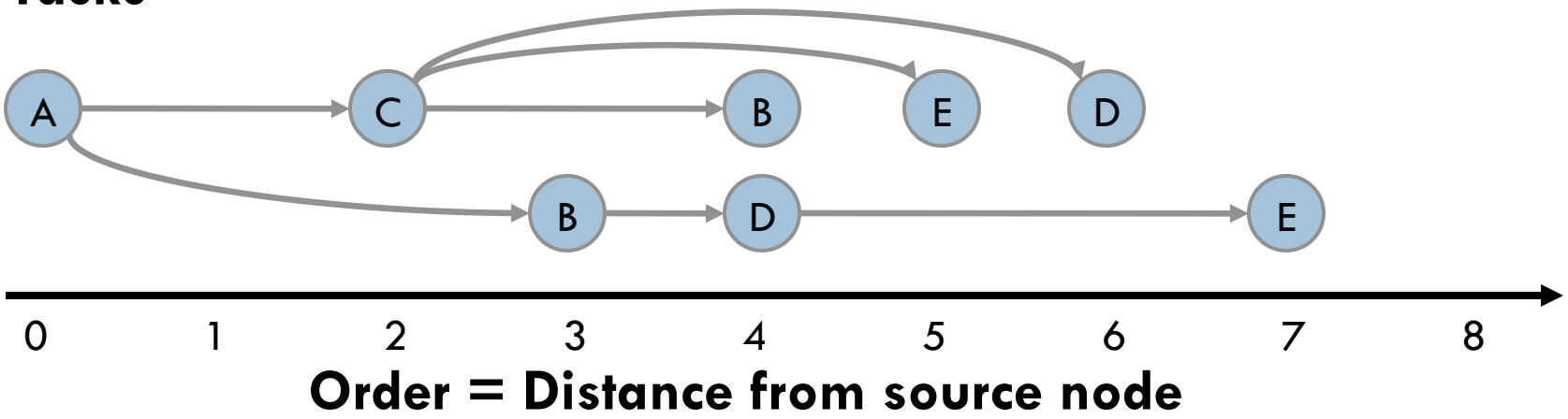
Example: Parallelism in Dijkstra's Algorithm

Finds shortest-path tree on a graph with weighted edges





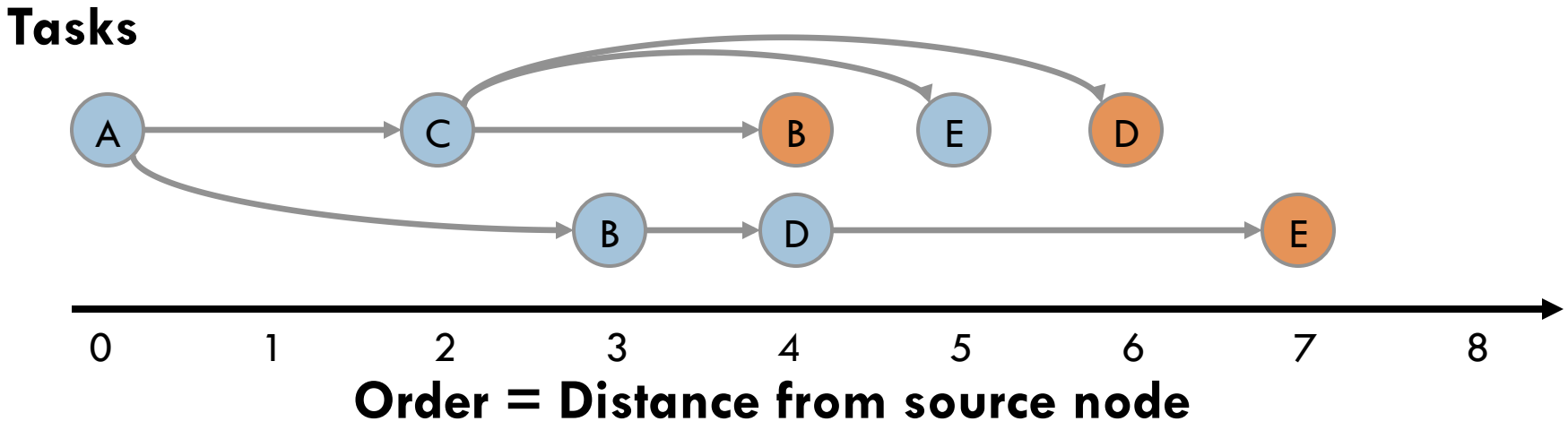
Tasks



Order = Distance from source node

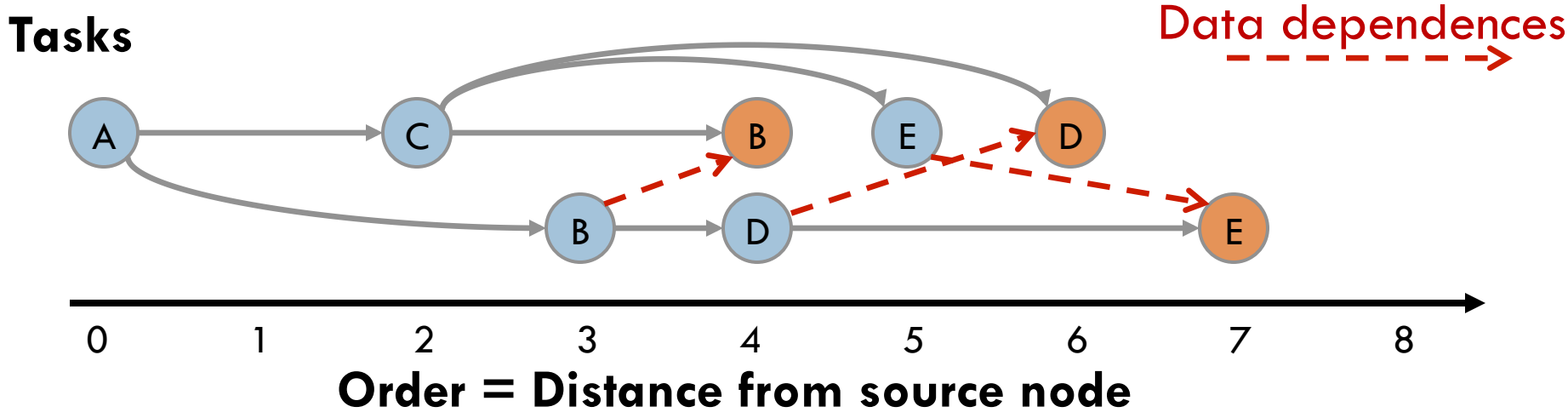
Parallelism in Dijkstra's Algorithm

Can execute independent tasks out of order



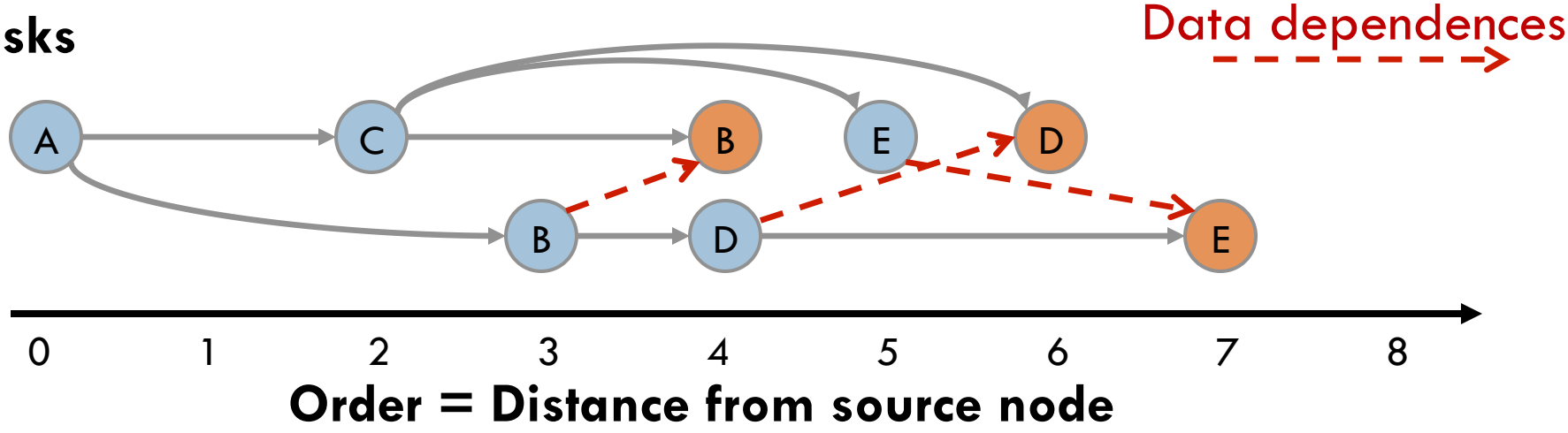
Parallelism in Dijkstra's Algorithm

Can execute independent tasks out of order

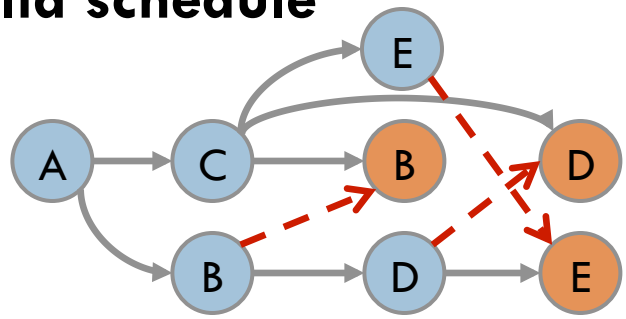


Parallelism in Dijkstra's Algorithm

Can execute independent tasks out of order

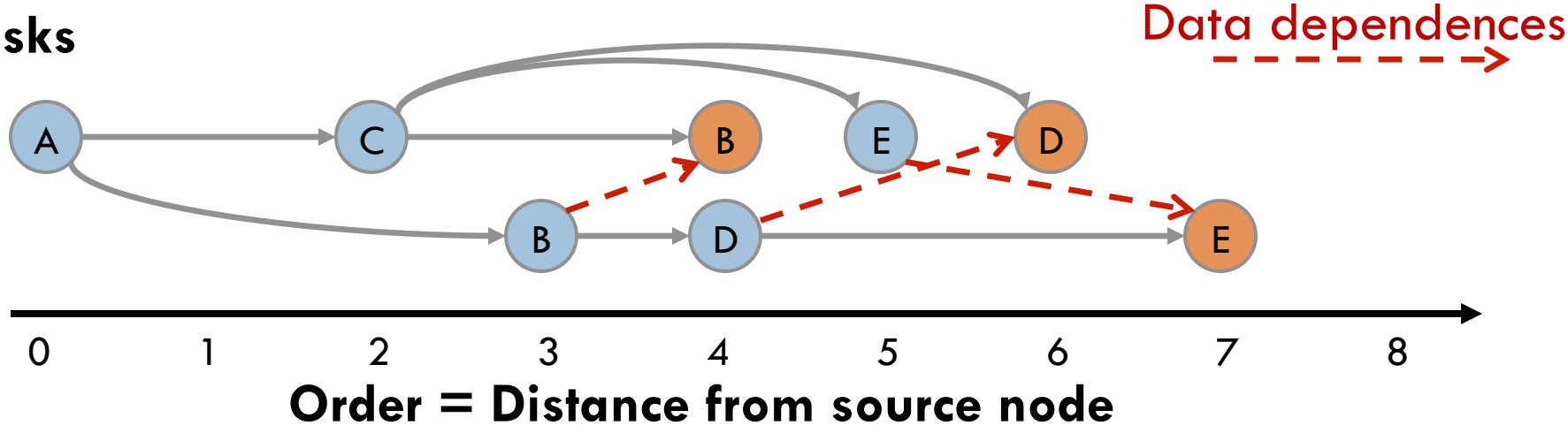


Valid schedule

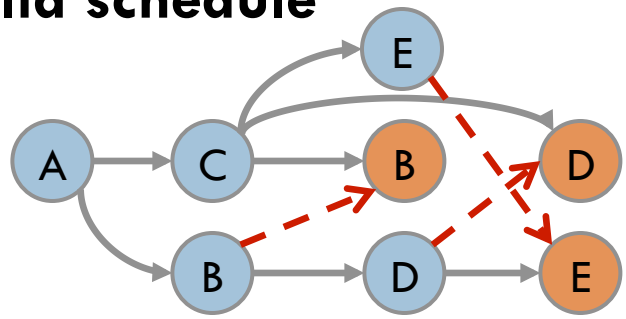


Parallelism in Dijkstra's Algorithm

Can execute independent tasks out of order



Valid schedule

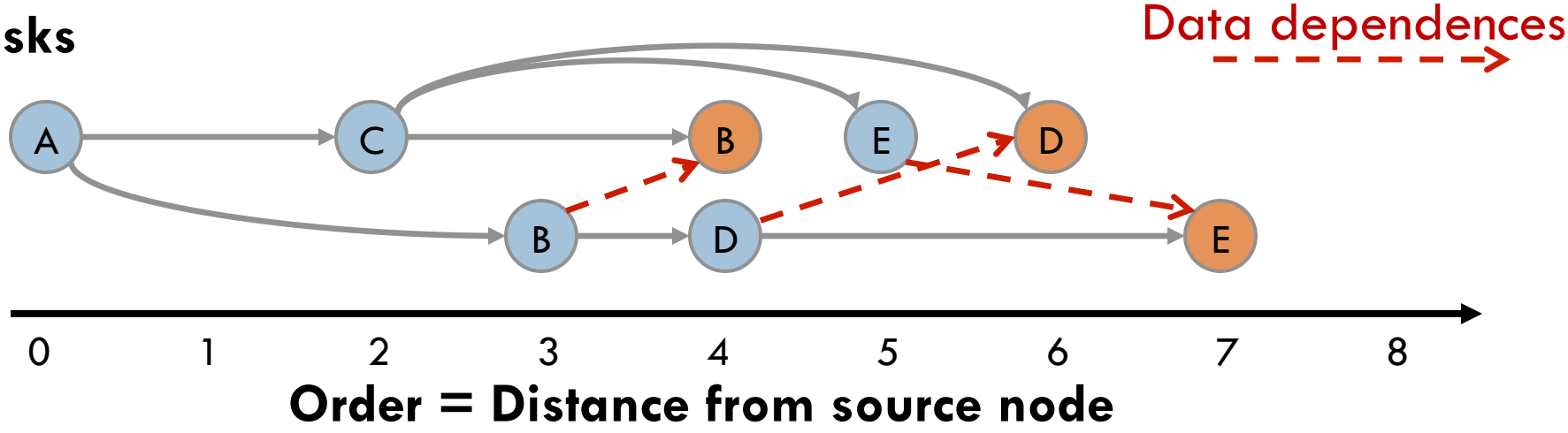


2x parallelism
(more in larger graphs)

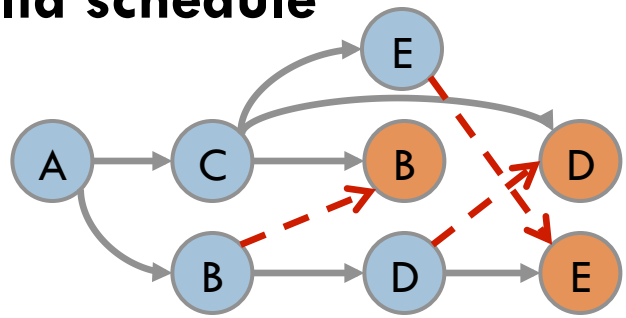
Tasks and dependences unknown in advance

Parallelism in Dijkstra's Algorithm

Can execute independent tasks out of order



Valid schedule



2x parallelism (more in larger graphs)

Tasks and dependences unknown in advance

Need speculative execution to elide order constraints

Insights about Ordered Parallelism

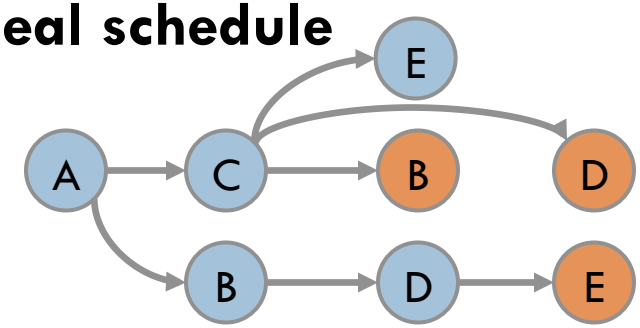
Insights about Ordered Parallelism

1. With perfect speculation, parallelism is plentiful

Insights about Ordered Parallelism

1. With perfect speculation, parallelism is plentiful

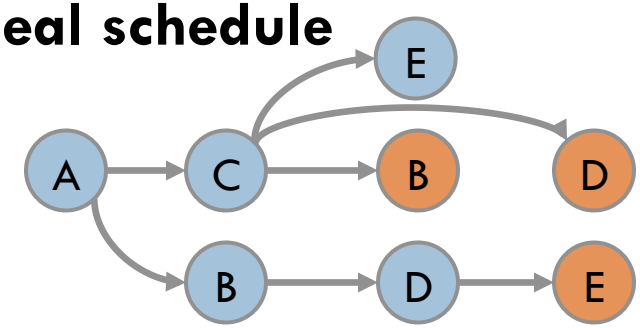
Ideal schedule



Insights about Ordered Parallelism

1. With perfect speculation, parallelism is plentiful

Ideal schedule



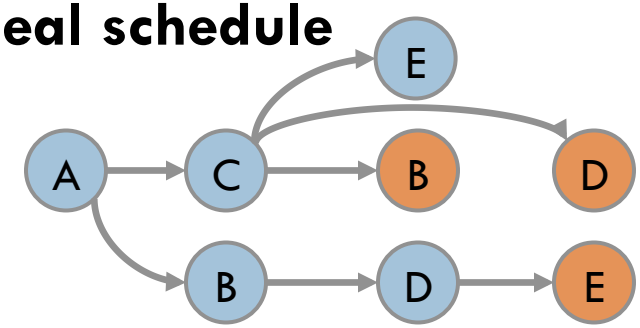
Parallelism

max 800x

Insights about Ordered Parallelism

1. With perfect speculation, parallelism is plentiful

Ideal schedule



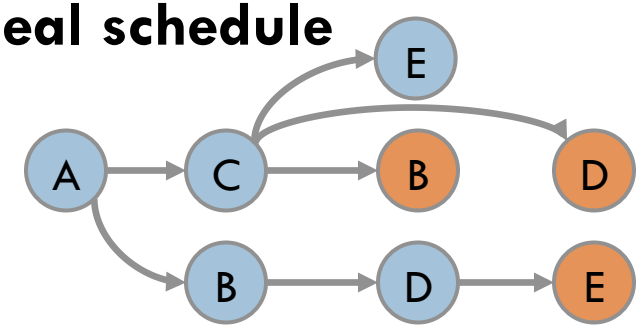
Parallelism

2. Tasks are tiny: 32 instructions on average

Insights about Ordered Parallelism

1. With perfect speculation, parallelism is plentiful

Ideal schedule



Parallelism

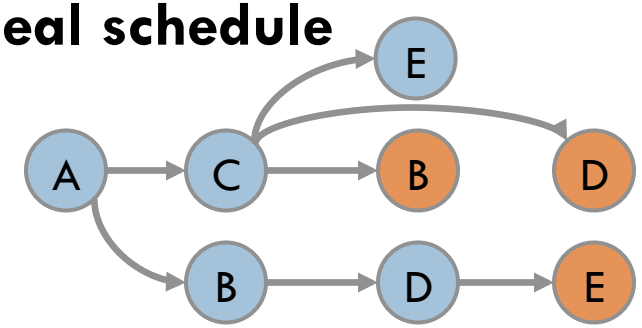
2. Tasks are tiny: 32 instructions on average

3. Independent tasks are far away in program order

Insights about Ordered Parallelism

1. With perfect speculation, parallelism is plentiful

Ideal schedule

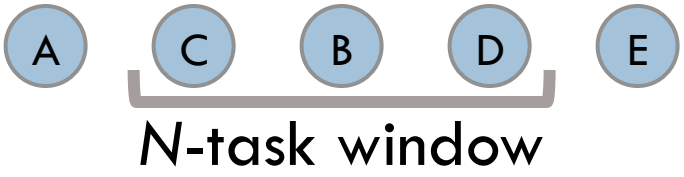


Parallelism

max 800x

2. Tasks are tiny: 32 instructions on average

3. Independent tasks are far away in program order

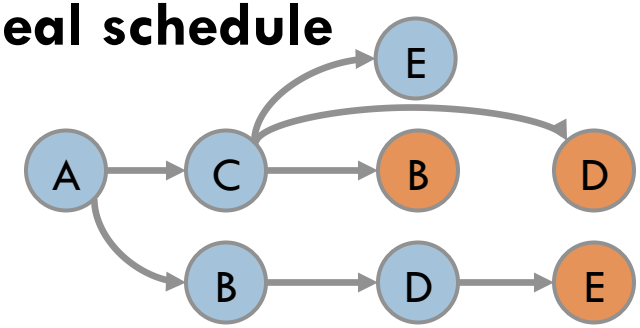


Can execute *N* tasks ahead of the earliest active task

Insights about Ordered Parallelism

1. With perfect speculation, parallelism is plentiful

Ideal schedule

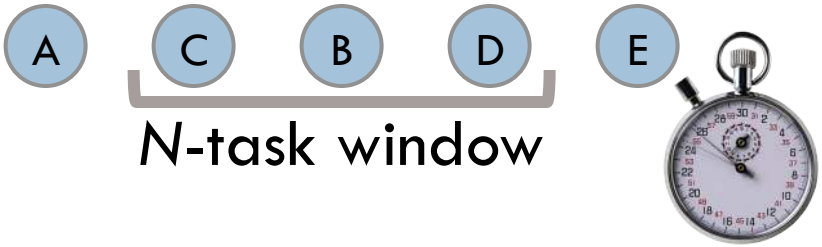


Parallelism

max 800x

2. Tasks are tiny: 32 instructions on average

3. Independent tasks are far away in program order

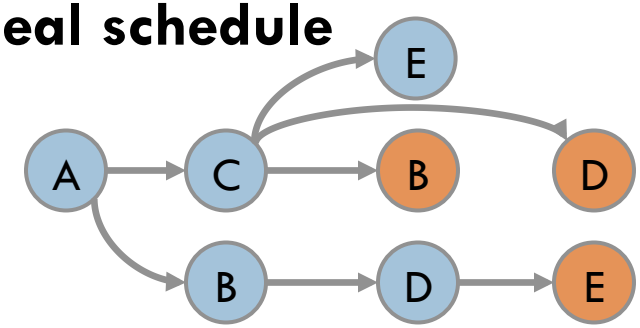


Can execute *N* tasks ahead of the earliest active task

Insights about Ordered Parallelism

1. With perfect speculation, parallelism is plentiful

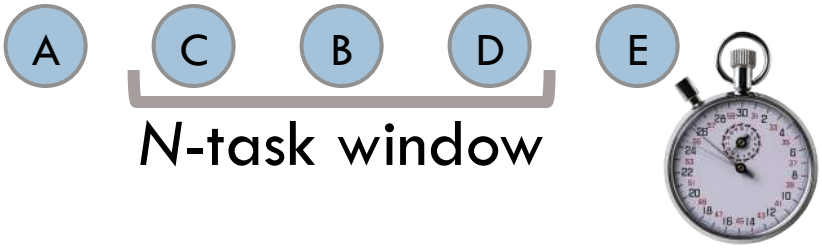
Ideal schedule



	Parallelism
max	800x
window=64	26x

2. Tasks are tiny: 32 instructions on average

3. Independent tasks are far away in program order

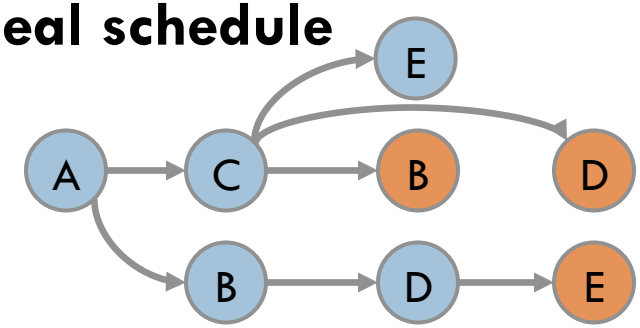


Can execute *N* tasks ahead of the earliest active task

Insights about Ordered Parallelism

1. With perfect speculation, parallelism is plentiful

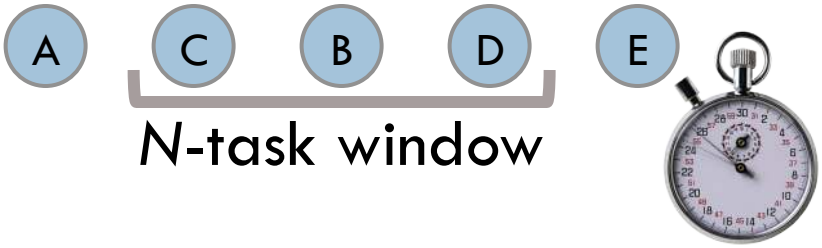
Ideal schedule



	Parallelism
max	800x
window=64	26x
window=1k	180x

2. Tasks are tiny: 32 instructions on average

3. Independent tasks are far away in program order

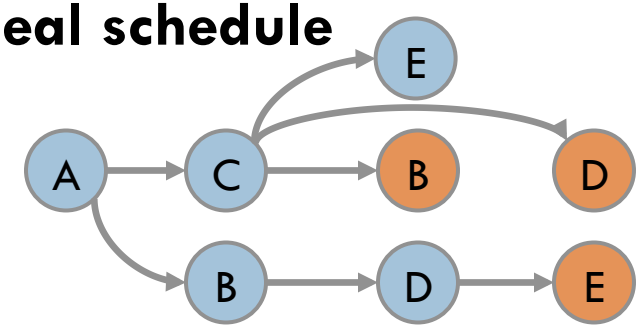


Can execute *N* tasks ahead of the earliest active task

Insights about Ordered Parallelism

1. With perfect speculation, parallelism is plentiful

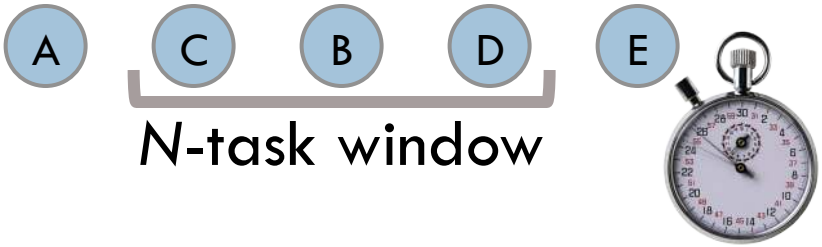
Ideal schedule



	Parallelism
max	800x
window=64	26x
window=1k	180x

2. Tasks are tiny: 32 instructions on average

3. Independent tasks are far away in program order



Can execute *N* tasks ahead of the earliest active task

Need a large window of speculation

Prior Work Can't Mine Ordered Parallelism

Prior Work Can't Mine Ordered Parallelism

- Thread-Level Speculation (TLS) parallelizes loops and function calls in sequential programs

Prior Work Can't Mine Ordered Parallelism

- Thread-Level Speculation (TLS) parallelizes loops and function calls in sequential programs

Max parallelism	TLS parallelism
800x	1.1x

Prior Work Can't Mine Ordered Parallelism

- Thread-Level Speculation (TLS) parallelizes loops and function calls in sequential programs

Max parallelism	TLS parallelism
800x	1.1x

Execution order ≠ creation order

Prior Work Can't Mine Ordered Parallelism

- Thread-Level Speculation (TLS) parallelizes loops and function calls in sequential programs

Max parallelism	TLS parallelism
800x	1.1x

Execution order ≠ creation order

Task-scheduling priority queues introduce false data dependences

Prior Work Can't Mine Ordered Parallelism

- Thread-Level Speculation (TLS) parallelizes loops and function calls in sequential programs

Max parallelism	TLS parallelism
800x	1.1x

Execution order ≠ creation order

Task-scheduling priority queues introduce false data dependences

- Sophisticated parallel algorithms yield limited speedup

Prior Work Can't Mine Ordered Parallelism

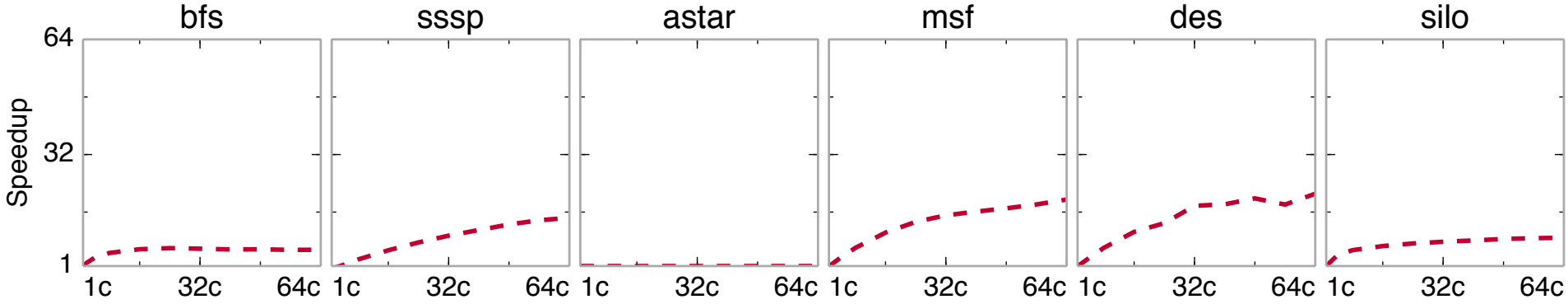
- Thread-Level Speculation (TLS) parallelizes loops and function calls in sequential programs

Max parallelism	TLS parallelism
800x	1.1x

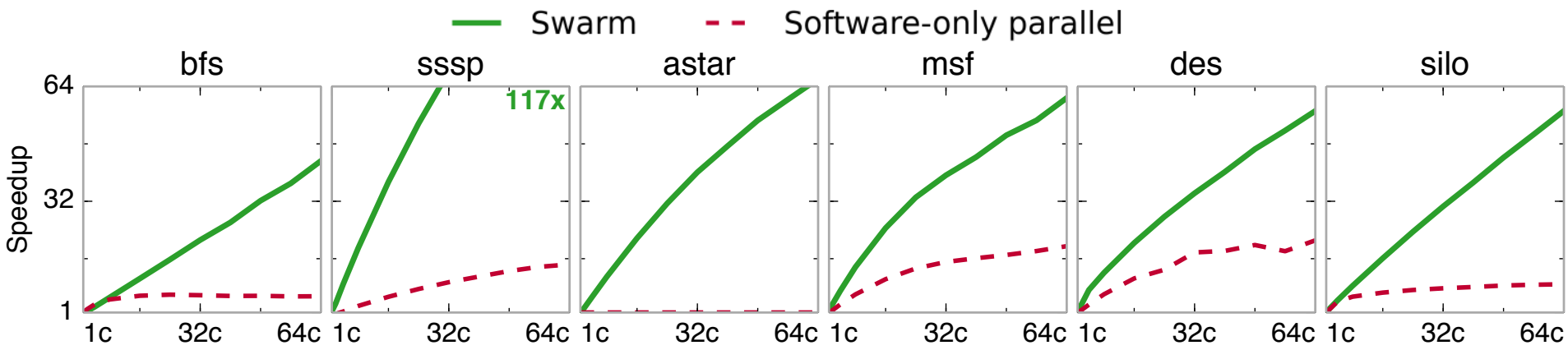
Execution order ≠ creation order

Task-scheduling priority queues introduce false data dependences

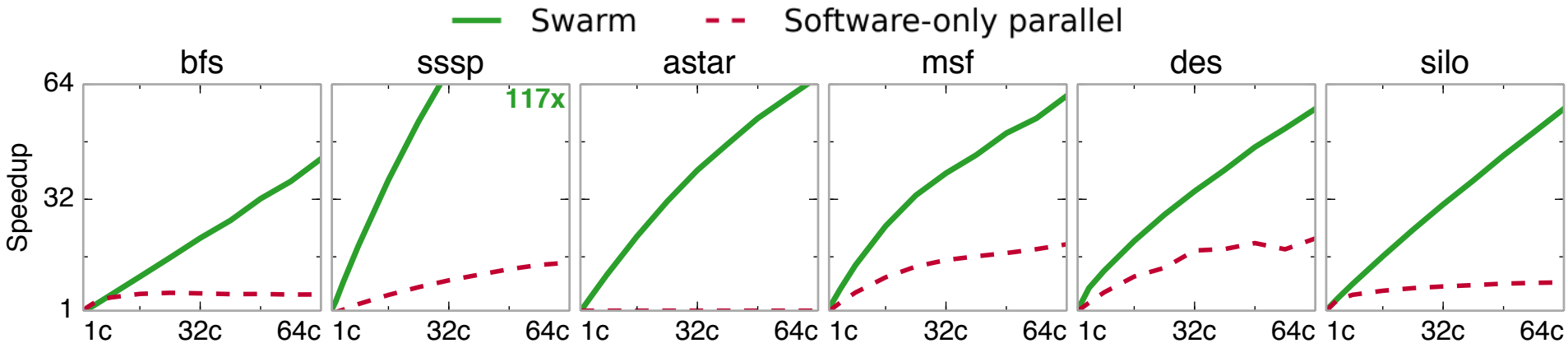
- Sophisticated parallel algorithms yield limited speedup



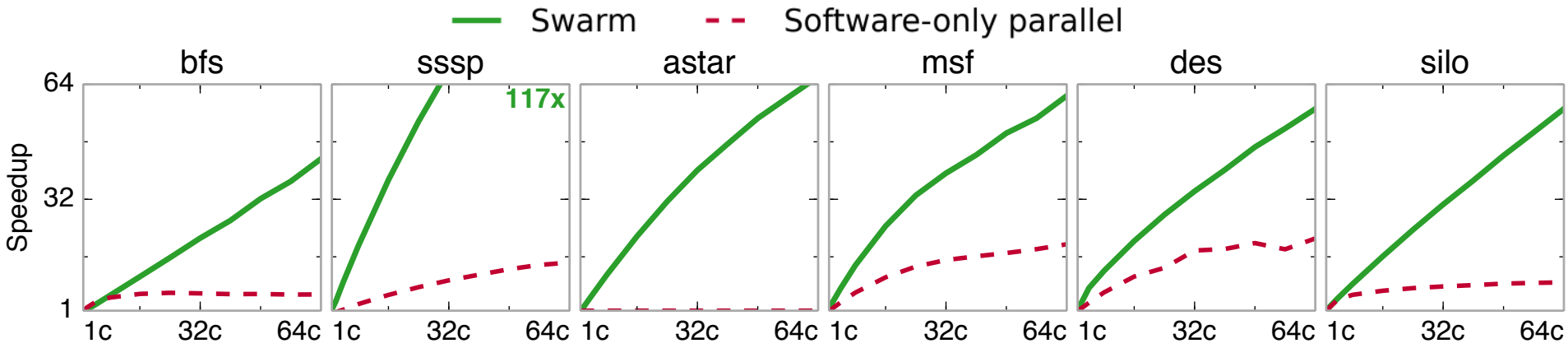
Swarm Mines Ordered Parallelism



Swarm Mines Ordered Parallelism

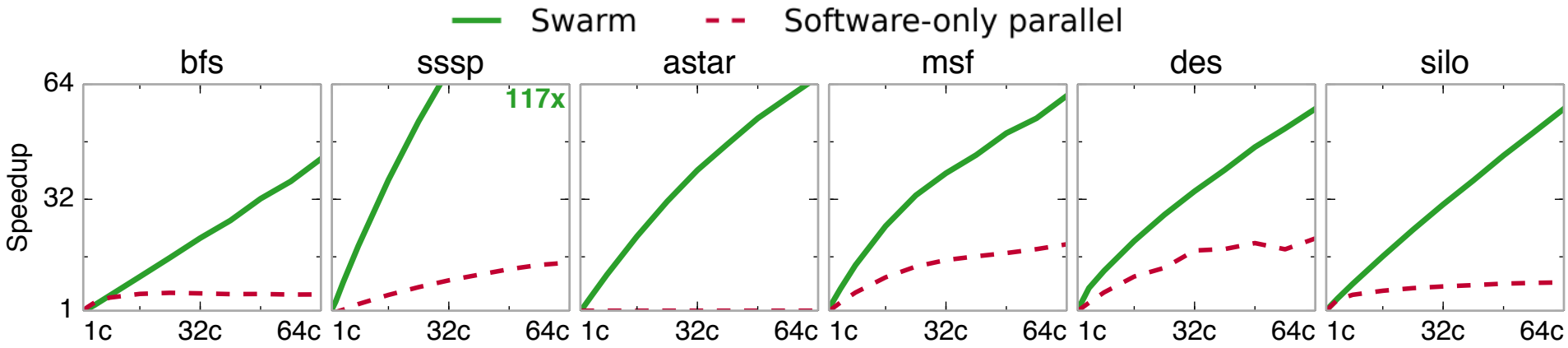


Swarm Mines Ordered Parallelism



- Execution model based on timestamped tasks

Swarm Mines Ordered Parallelism



- Execution model based on timestamped tasks
- Architecture executes tasks speculatively out of order
  - Leverages execution model to scale

Outline

- Understanding Ordered Parallelism
- Swarm
- Evaluation

Swarm Execution Model

Programs consist of timestamped tasks

Swarm Execution Model

Programs consist of timestamped tasks

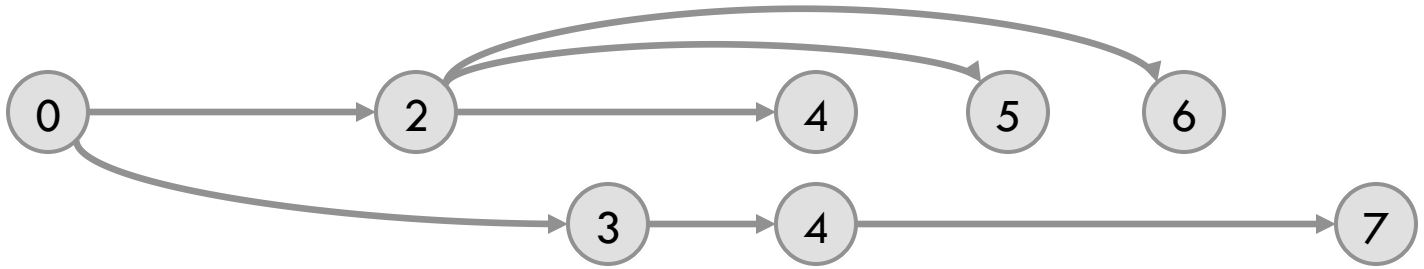
- Tasks can create children tasks with >= timestamp
- Tasks appear to execute in timestamp order

Swarm Execution Model

Programs consist of timestamped tasks

- Tasks can create children tasks with >= timestamp
- Tasks appear to execute in timestamp order
- Programmed with implicitly-parallel task API

```
swarm::enqueue(fptr, ts, args...);
```

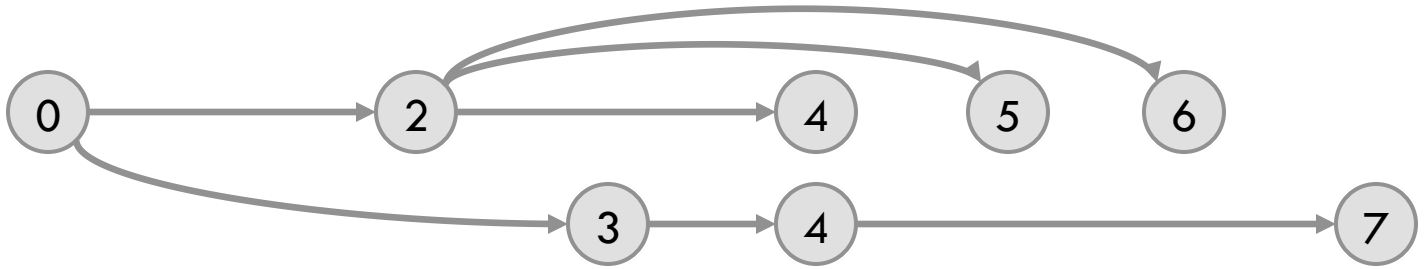


Swarm Execution Model

Programs consist of timestamped tasks

- Tasks can create children tasks with >= timestamp
- Tasks appear to execute in timestamp order
- Programmed with implicitly-parallel task API

```
swarm::enqueue(fptr, ts, args...);
```



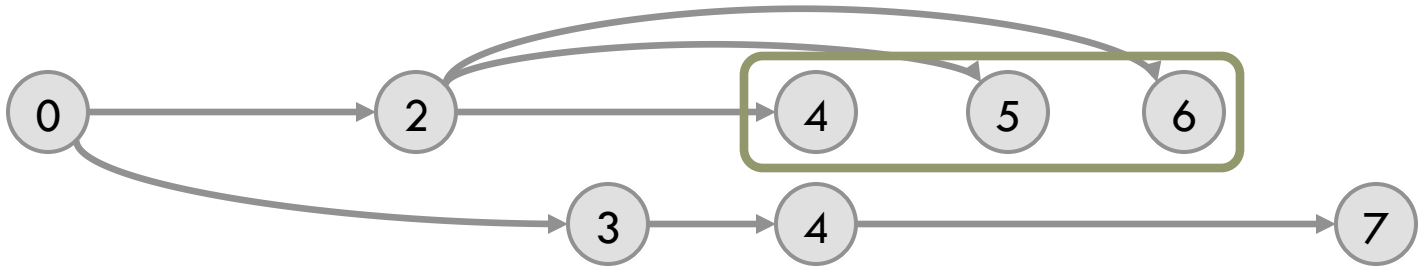
Conveys new work to hardware as soon as possible

Swarm Execution Model

Programs consist of timestamped tasks

- Tasks can create children tasks with >= timestamp
- Tasks appear to execute in timestamp order
- Programmed with implicitly-parallel task API

```
swarm::enqueue(fptr, ts, args...);
```



Conveys new work to hardware as soon as possible

Swarm Task Example: Dijkstra


```
void ssspTask(Timestamp dist, Vertex& v) {
  if (!v.isVisited()) {
    v.distance = dist;
    for (Vertex& u : v.neighbors) {
       Timestamp uDist = dist + edgeWeight(v, u);
       swarm::enqueue(&ssspTask, uDist, u);
    }
  }
}
```

Swarm Task Example: Dijkstra


```
void ssspTask(Timestamp dist, Vertex& v) {
  if (!v.isVisited()) {
    v.distance = dist;
    for (Vertex& u : v.neighbors) {
      Timestamp uDist = dist + edgeWeight(v, u);
      swarm::enqueue(&ssspTask, uDist, u);
    }
  }
}
```

Swarm Task Example: Dijkstra


```
void ssspTask(Timestamp dist, Vertex& v) {
  if (!v.isVisited()) {
    v.distance = dist;
    for (Vertex& u : v.neighbors) {
      Timestamp uDist = dist + edgeWeight(v, u);
      swarm::enqueue(&ssspTask, uDist, u);
    }
  }
}
```

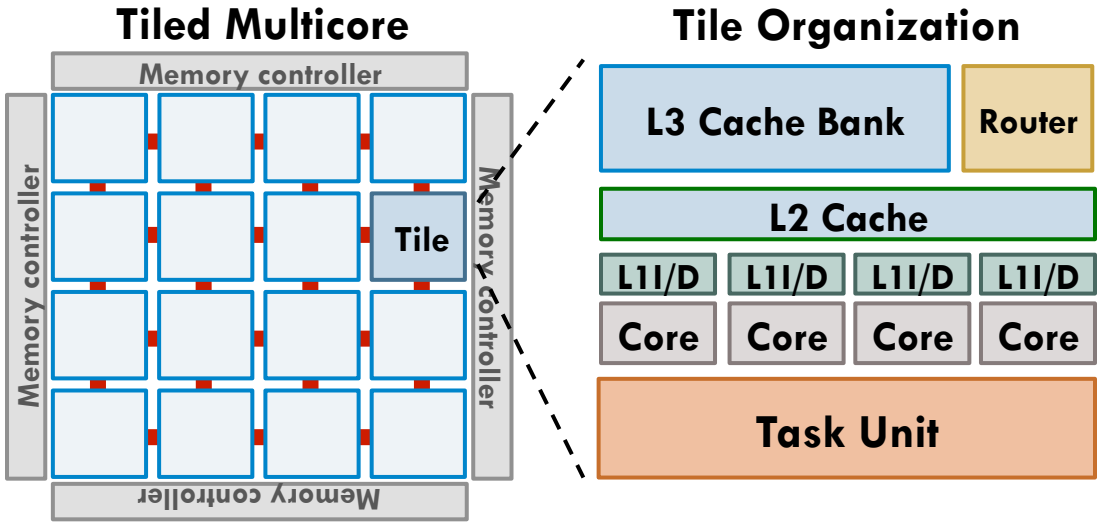
Timestamp

Swarm Task Example: Dijkstra

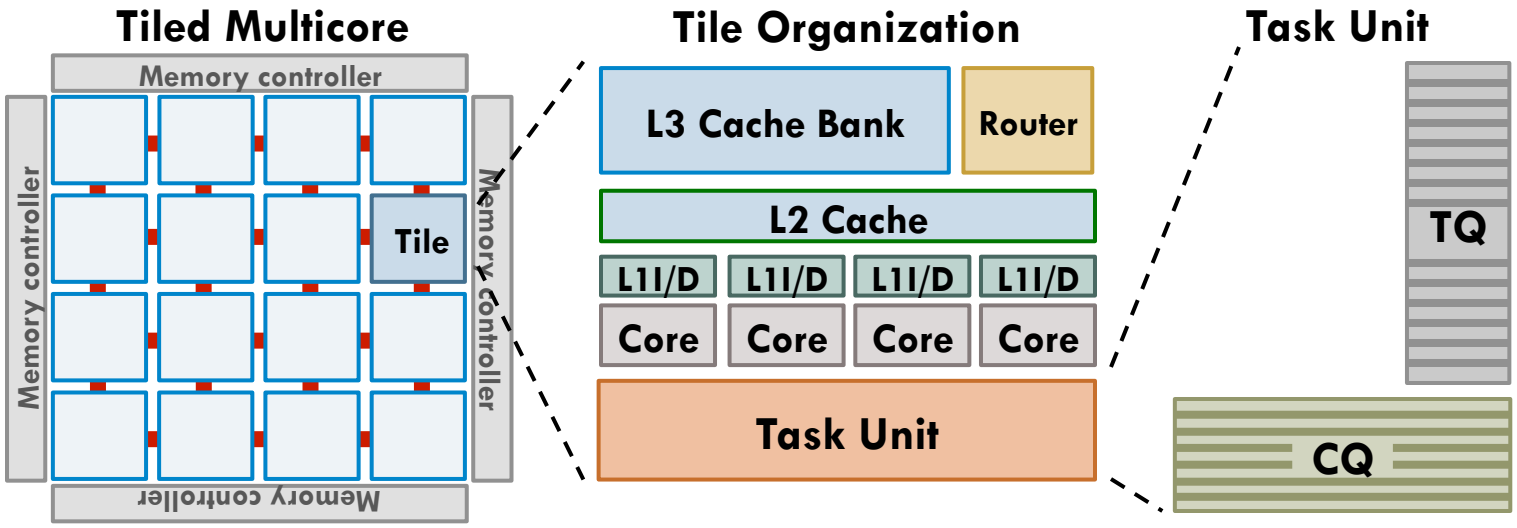

```
void ssspTask(Timestamp dist, Vertex& v) {
  if (!v.isVisited()) {
    v.distance = dist;
    for (Vertex& u : v.neighbors) {
      Timestamp uDist = dist + edgeWeight(v, u);
      swarm::enqueue(&ssspTask, uDist, u);
    }
  }
}

swarm::enqueue(ssspTask, 0, sourceVertex);
swarm::run();
```

Swarm Architecture Overview



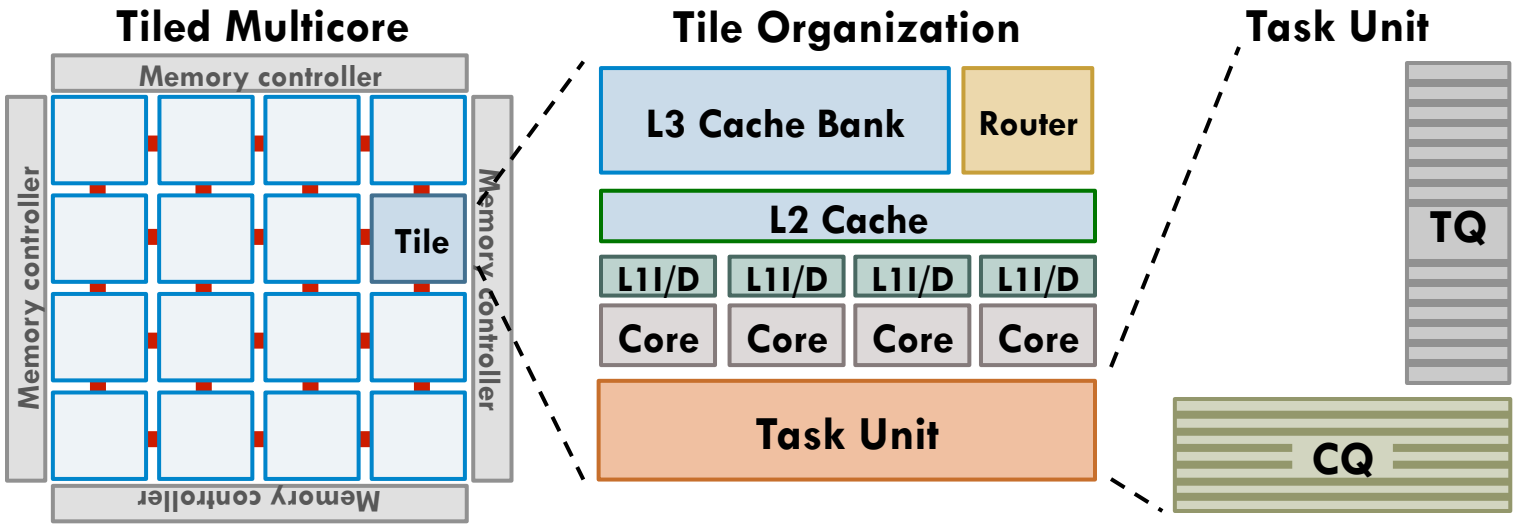
Swarm Architecture Overview



Per-tile task units:

- **Task Queue:** holds task descriptors
- **Commit Queue:** holds speculative state of finished tasks

Swarm Architecture Overview



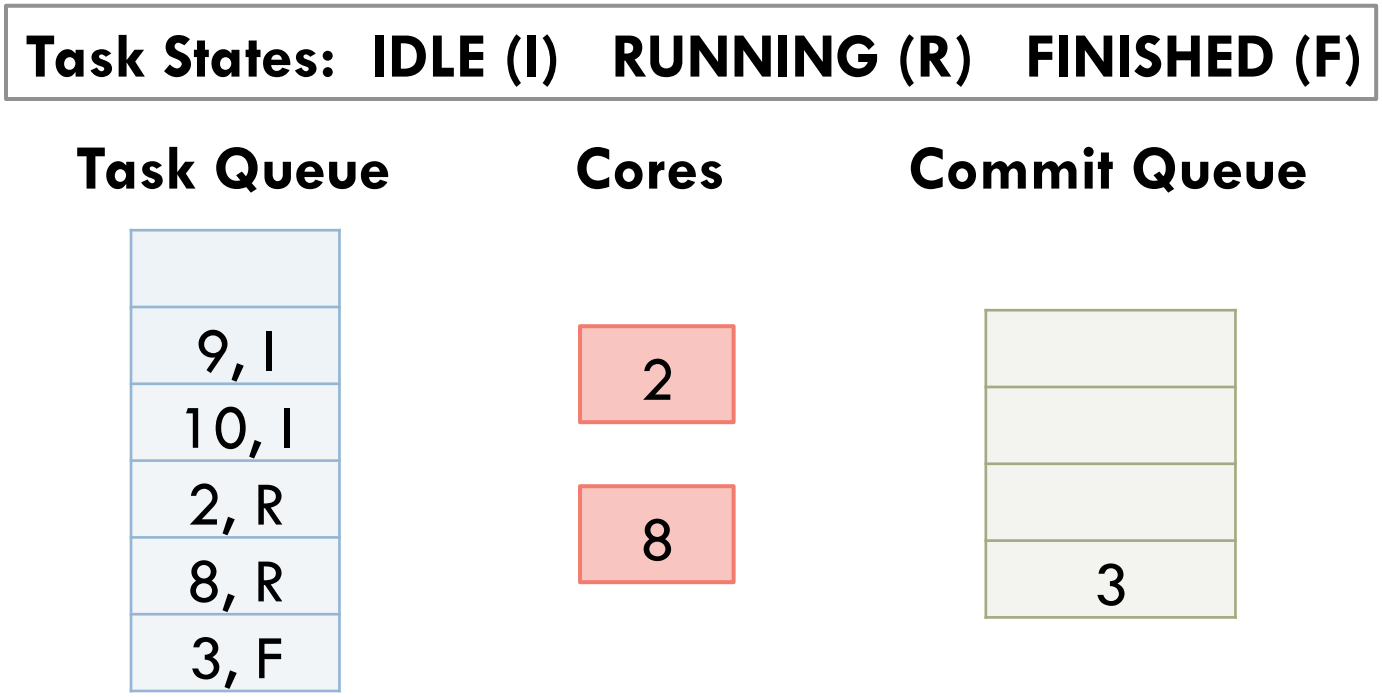
Per-tile task units:

- **Task Queue:** holds task descriptors
- **Commit Queue:** holds speculative state of finished tasks

Commit queues provide the window of speculation

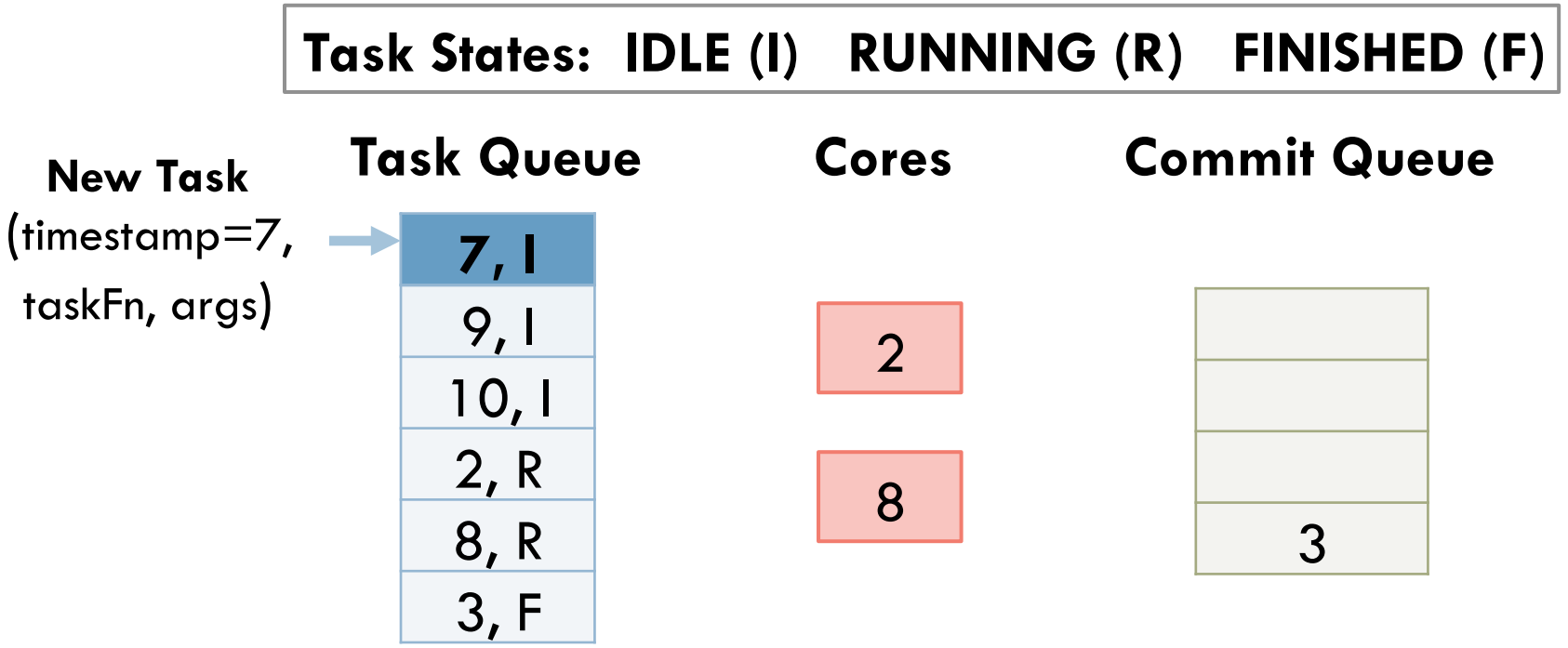
Task Unit Queues

- **Task queue**: holds task descriptors
- **Commit Queue**: holds speculative state of finished tasks



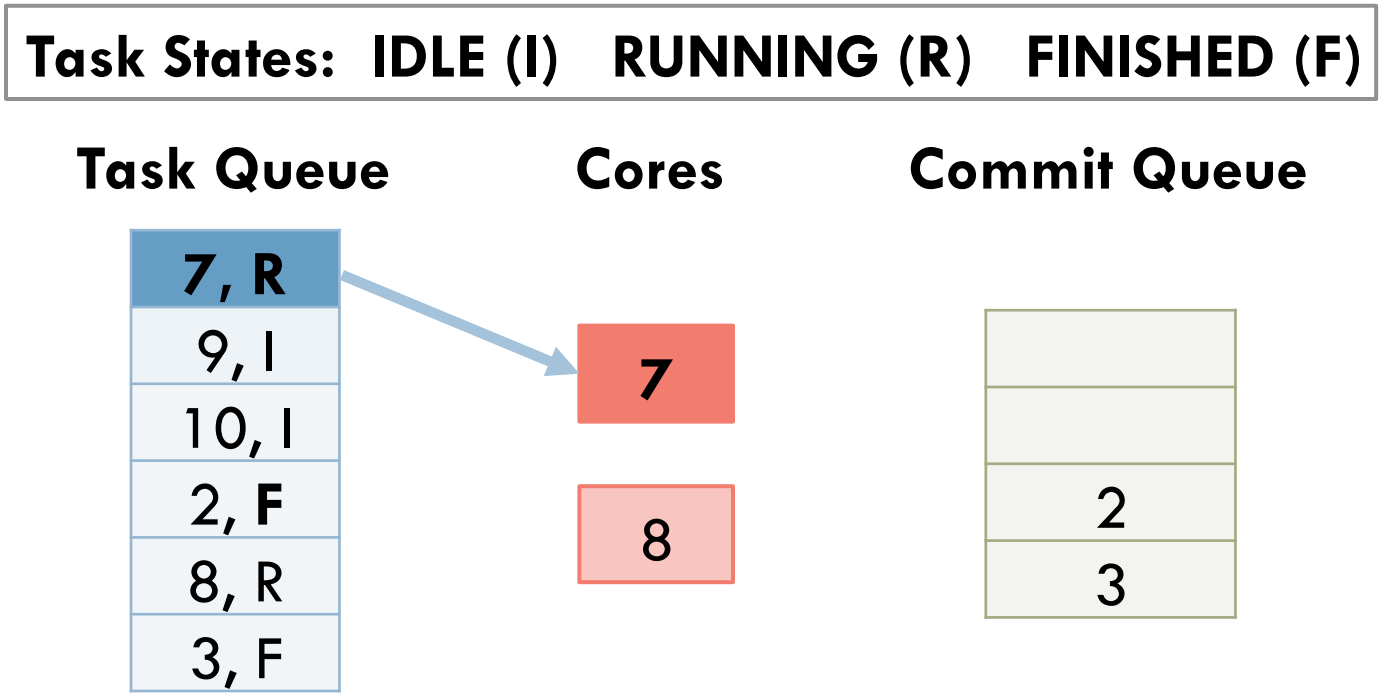
Task Unit Queues

- **Task queue**: holds task descriptors
- **Commit Queue**: holds speculative state of finished tasks



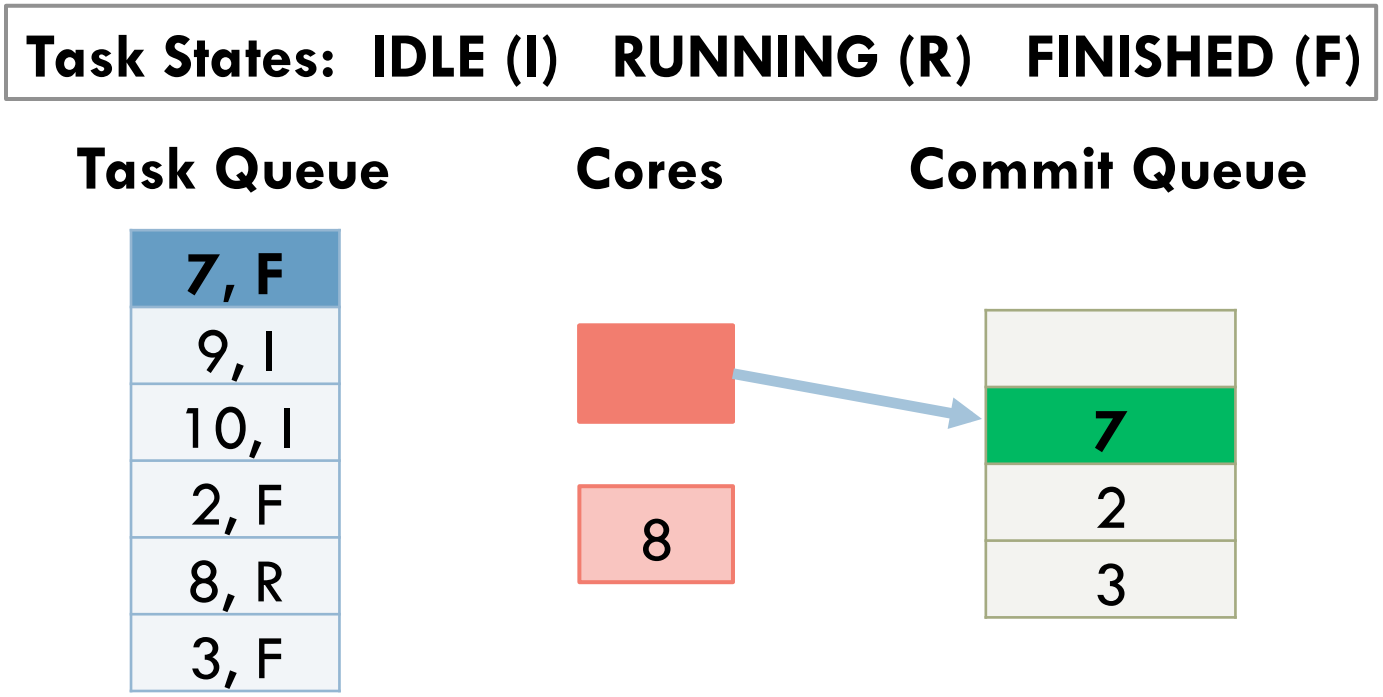
Task Unit Queues

- **Task queue**: holds task descriptors
- **Commit Queue**: holds speculative state of finished tasks



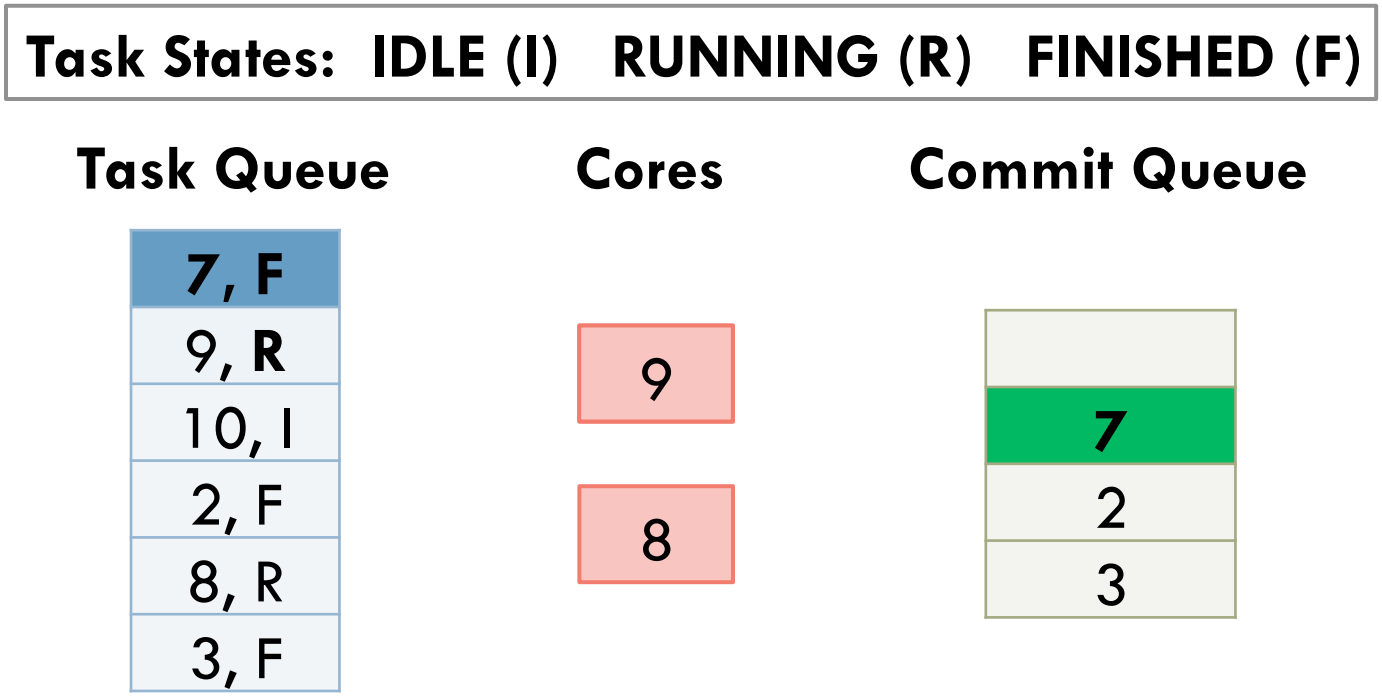
Task Unit Queues

- **Task queue**: holds task descriptors
- **Commit Queue**: holds speculative state of finished tasks



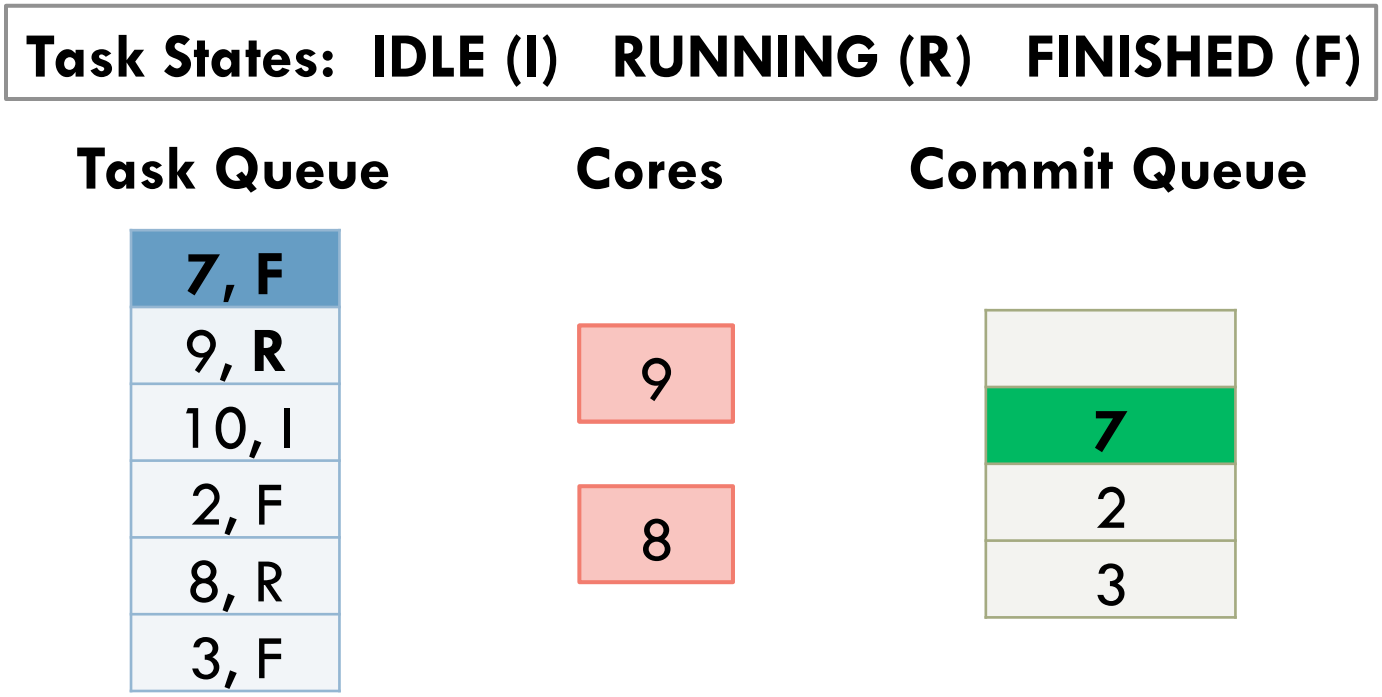
Task Unit Queues

- **Task queue**: holds task descriptors
- **Commit Queue**: holds speculative state of finished tasks



Task Unit Queues

- **Task queue**: holds task descriptors
- **Commit Queue**: holds speculative state of finished tasks



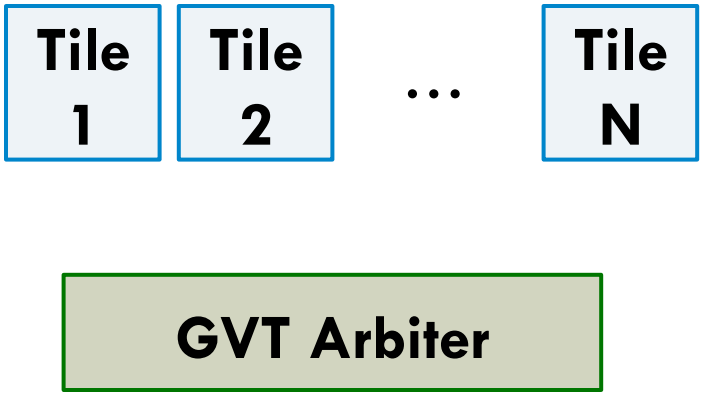
Similar to a reorder buffer, but at the task level

High-Throughput Ordered Commits

- Suppose 64-cycle tasks execute on 64 cores
  - **1 task commit/cycle** to scale
  - TLS commit schemes (successor lists, commit token) too slow

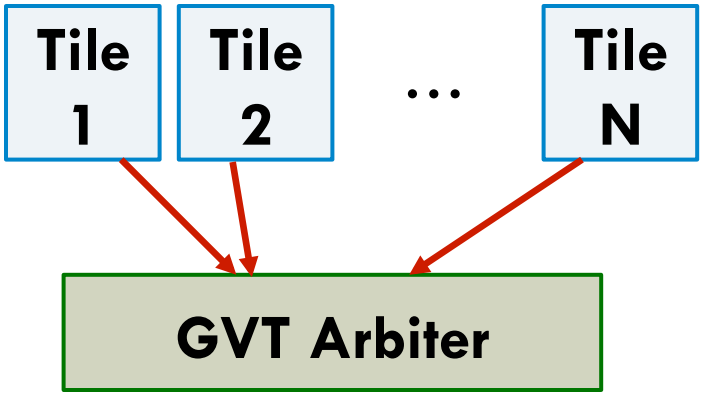
High-Throughput Ordered Commits

- Suppose 64-cycle tasks execute on 64 cores
  - **1 task commit/cycle** to scale
  - TLS commit schemes (successor lists, commit token) too slow
- We adapt "Virtual Time" [Jefferson, TOPLAS 1985]



High-Throughput Ordered Commits

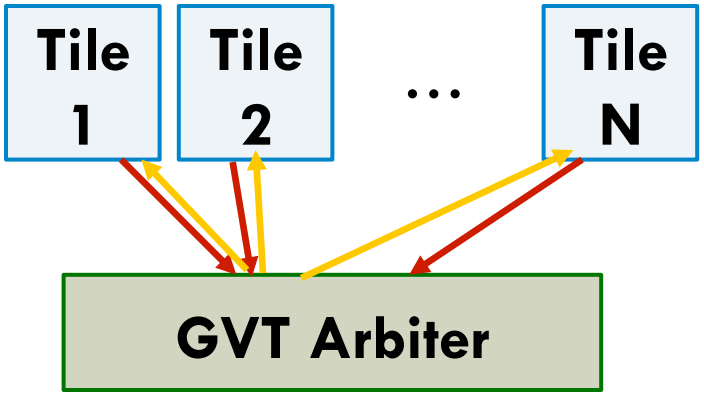
- Suppose 64-cycle tasks execute on 64 cores
  - **1 task commit/cycle** to scale
  - TLS commit schemes (successor lists, commit token) too slow
- We adapt "Virtual Time" [Jefferson, TOPLAS 1985]



- Tiles periodically communicate to find the earliest unfinished task

High-Throughput Ordered Commits

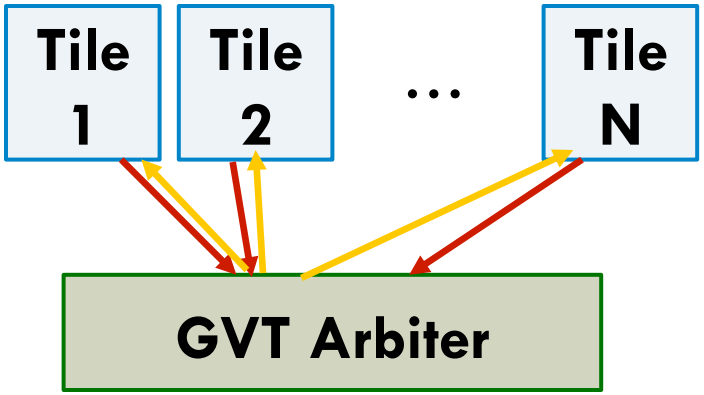
- Suppose 64-cycle tasks execute on 64 cores
  - **1 task commit/cycle** to scale
  - TLS commit schemes (successor lists, commit token) too slow
- We adapt "Virtual Time" [Jefferson, TOPLAS 1985]



- Tiles periodically communicate to find the earliest unfinished task

High-Throughput Ordered Commits

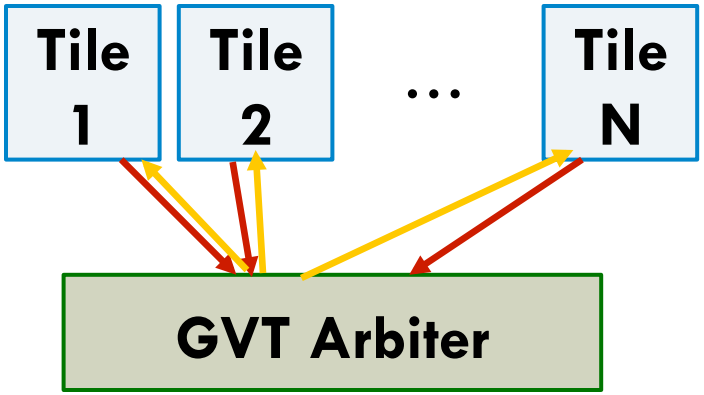
- Suppose 64-cycle tasks execute on 64 cores
  - **1 task commit/cycle** to scale
  - TLS commit schemes (successor lists, commit token) too slow
- We adapt "Virtual Time" [Jefferson, TOPLAS 1985]



- Tiles periodically communicate to find the earliest unfinished task
- Tiles commit all tasks that precede it

High-Throughput Ordered Commits

- Suppose 64-cycle tasks execute on 64 cores
  - **1 task commit/cycle** to scale
  - TLS commit schemes (successor lists, commit token) too slow
- We adapt "Virtual Time" [Jefferson, TOPLAS 1985]

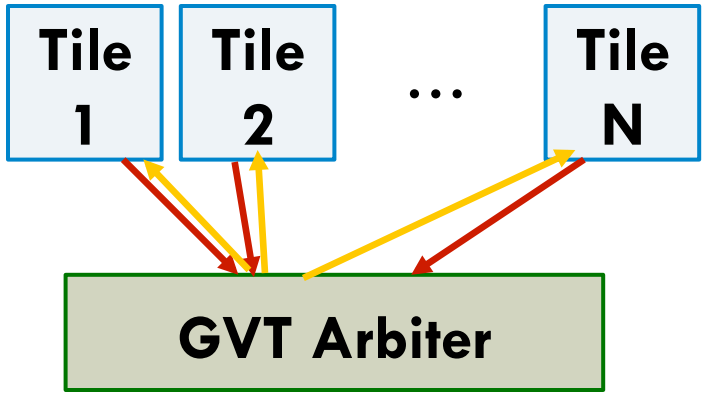


- Tiles periodically communicate to find the earliest unfinished task
- Tiles commit all tasks that precede it

With large commit queues, many tasks commit at once

High-Throughput Ordered Commits

- Suppose 64-cycle tasks execute on 64 cores
  - **1 task commit/cycle** to scale
  - TLS commit schemes (successor lists, commit token) too slow
- We adapt "Virtual Time" [Jefferson, TOPLAS 1985]

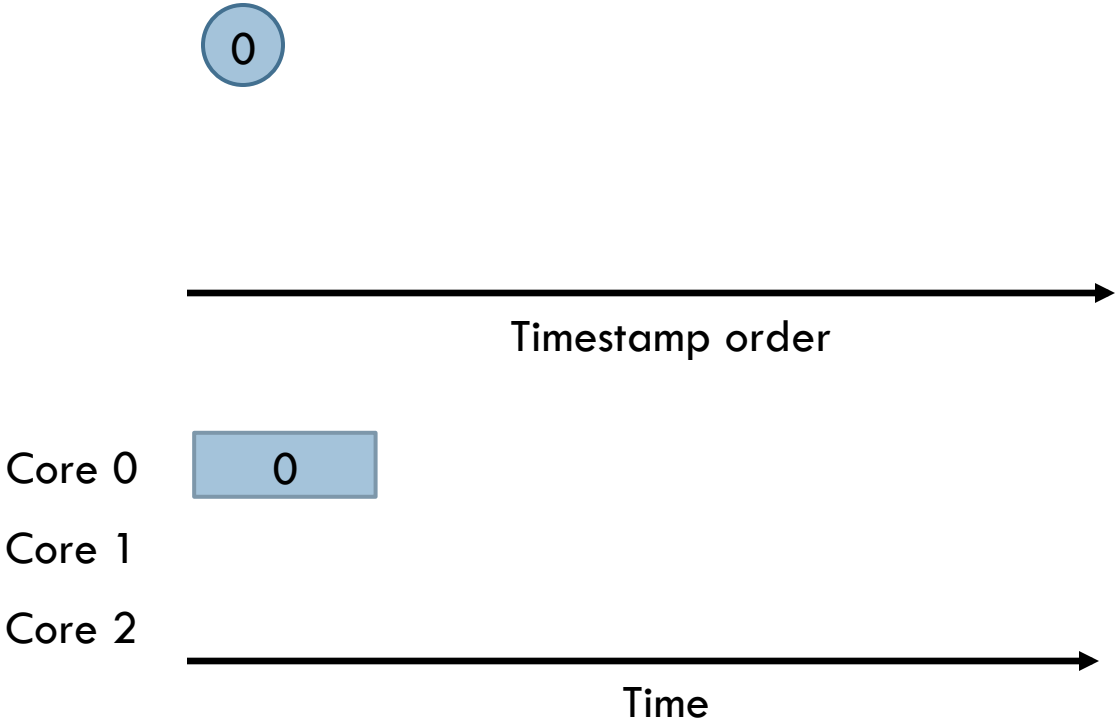


- Tiles periodically communicate to find the earliest unfinished task
- Tiles commit all tasks that precede it

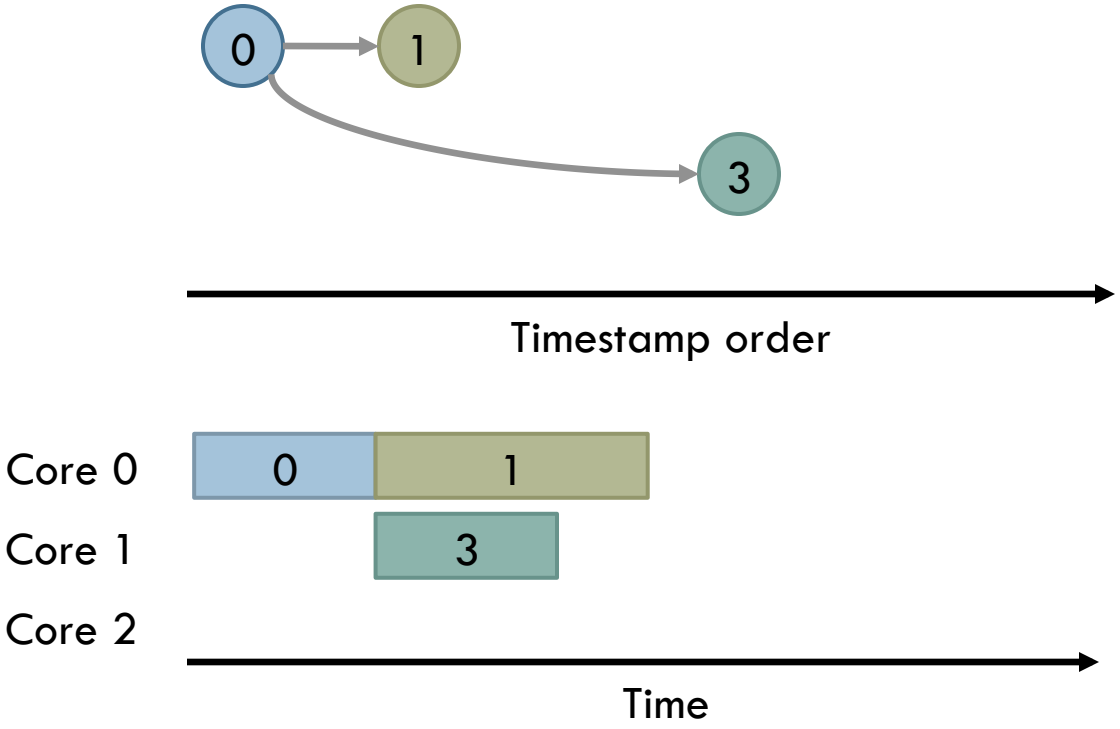
With large commit queues, many tasks commit at once

Amortizes commit costs among many tasks

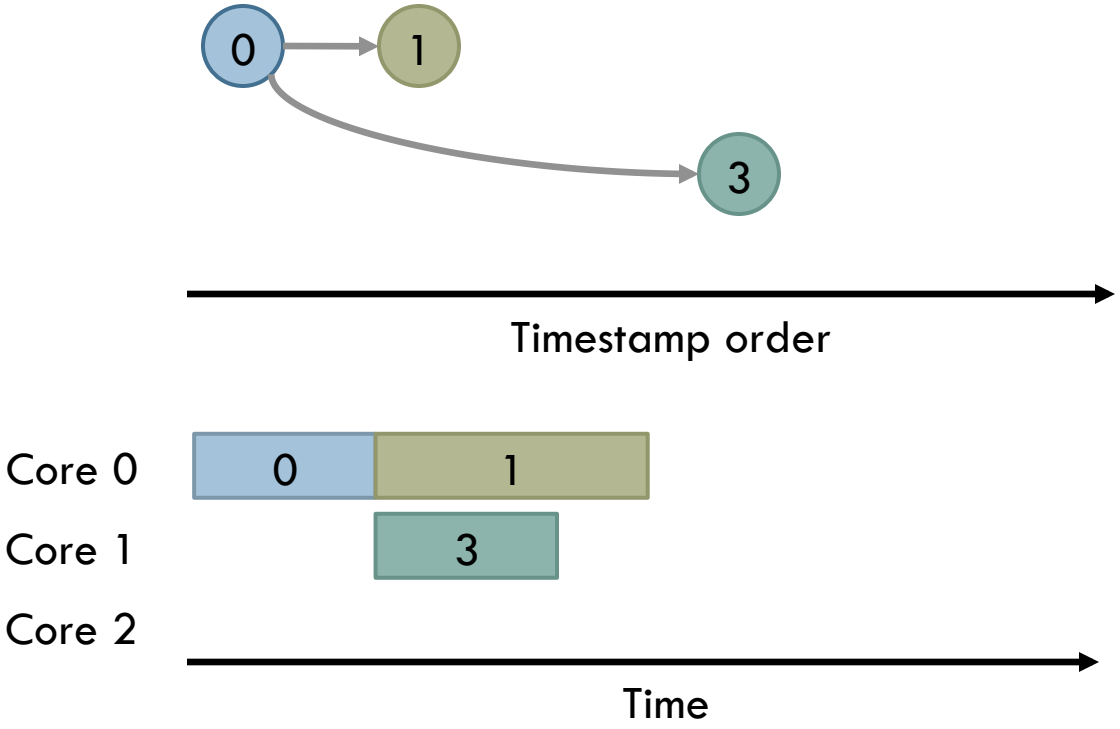
Speculative Execution Example



Speculative Execution Example

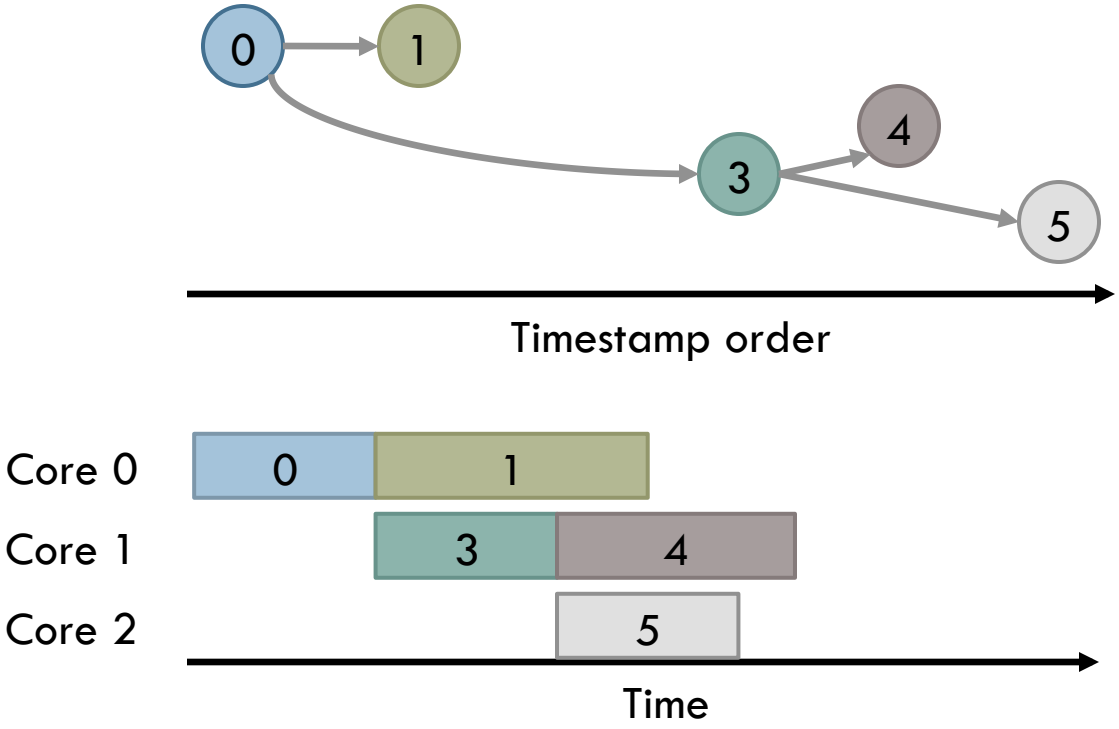


Speculative Execution Example



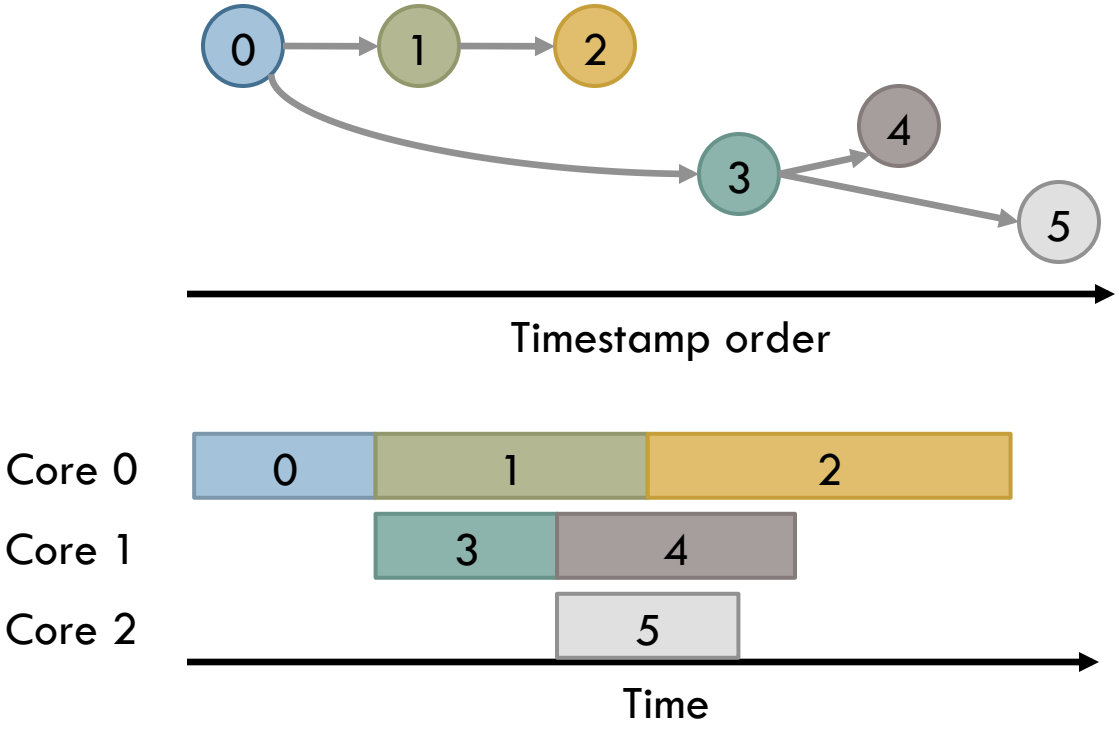
- Tasks can execute even if parent is still speculative
  - Uncovers more parallelism

Speculative Execution Example



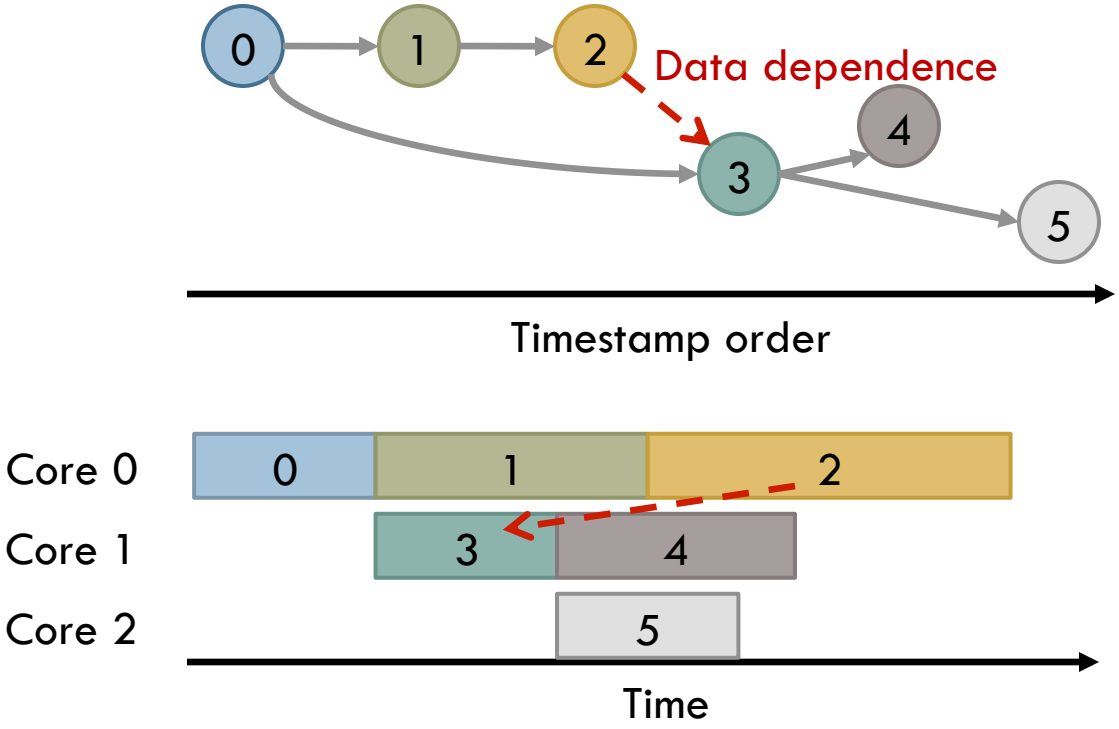
- Tasks can execute even if parent is still speculative
  - Uncovers more parallelism

Speculative Execution Example



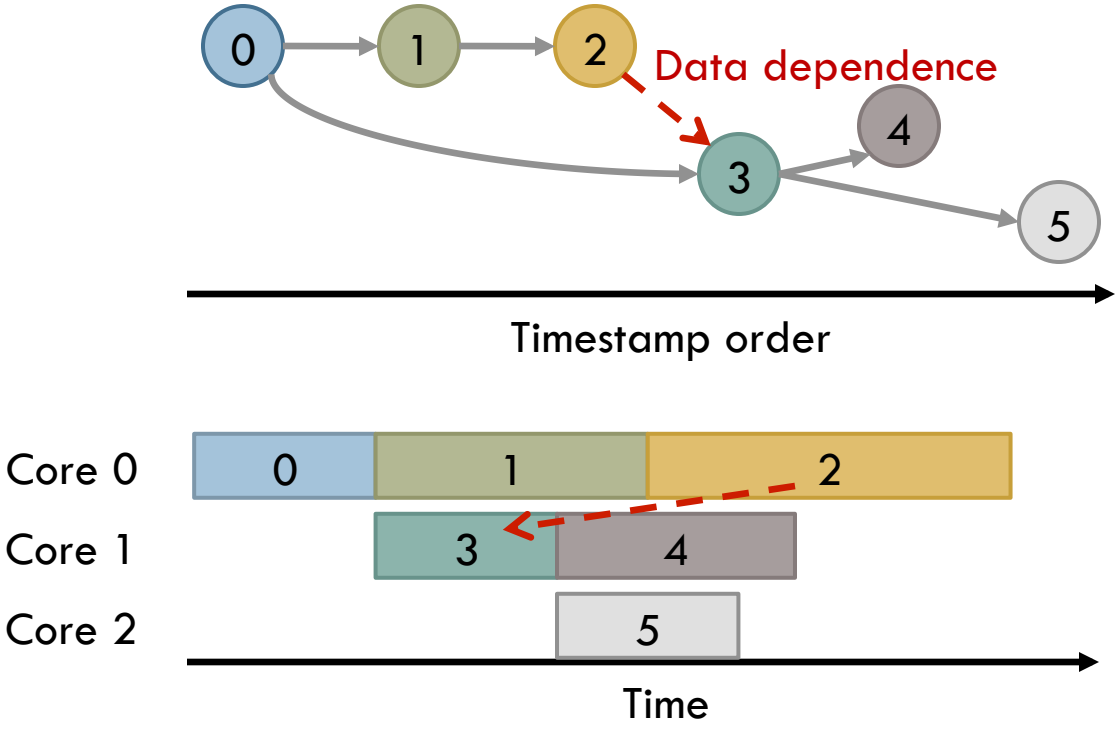
- Tasks can execute even if parent is still speculative
  - Uncovers more parallelism

Speculative Execution Example



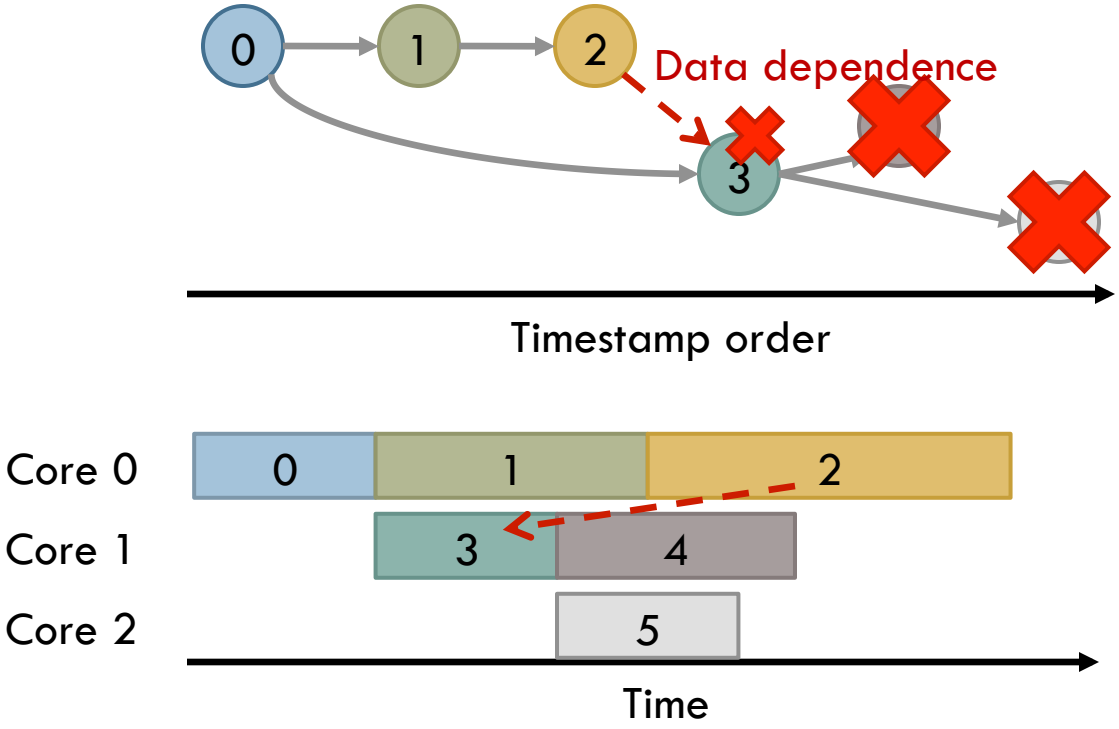
- Tasks can execute even if parent is still speculative
  - Uncovers more parallelism

Speculative Execution Example



- Tasks can execute even if parent is still speculative
  - Uncovers more parallelism
  - May trigger cascading (but selective) aborts

Speculative Execution Example



- Tasks can execute even if parent is still speculative
  - Uncovers more parallelism
  - May trigger cascading (but selective) aborts

Swarm Speculation Mechanisms

- Key requirements for speculative execution:
  - Fast commits
  - Large speculative window → Small per-task speculative state

Swarm Speculation Mechanisms

- Key requirements for speculative execution:
  - Fast commits
  - Large speculative window → Small per-task speculative state

- Eager versioning + timestamp-based conflict detection
  - Bloom filters for cheap read/write sets [Yen, HPCA 2007]

Swarm Speculation Mechanisms

- Key requirements for speculative execution:
  - Fast commits
  - Large speculative window → Small per-task speculative state

- Eager versioning + timestamp-based conflict detection
  - Bloom filters for cheap read/write sets [Yen, HPCA 2007]
  - Uses hierarchical memory system to filter conflict checks

Swarm Speculation Mechanisms

- Key requirements for speculative execution:
  - Fast commits
  - Large speculative window → Small per-task speculative state

- Eager versioning + timestamp-based conflict detection
  - Bloom filters for cheap read/write sets [Yen, HPCA 2007]
  - Uses hierarchical memory system to filter conflict checks

- Enables two helpful properties
  1. **Forwarding** of still-speculative data
  2. On rollback, corrective writes **abort dependent tasks only**

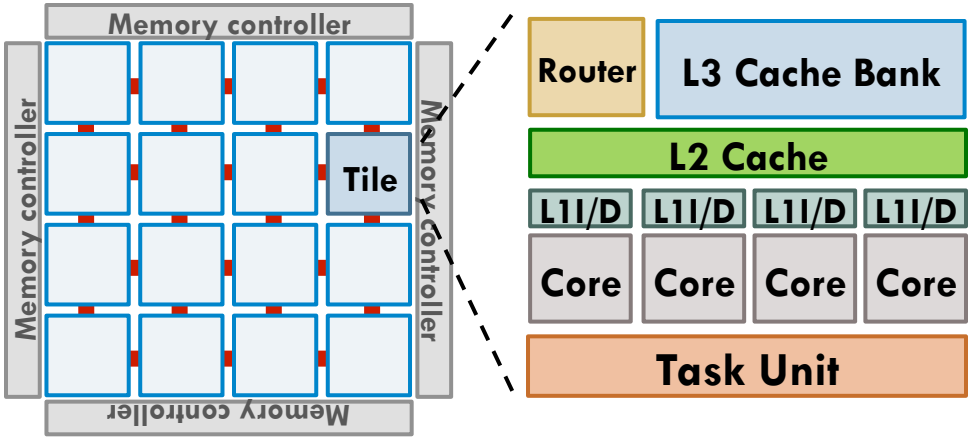
Outline

- Understanding Ordered Parallelism
- Swarm
- Evaluation

Evaluation Methodology

- Event-driven, sequential, Pin-based simulator

- Target system: 64-core, 16-tile chip



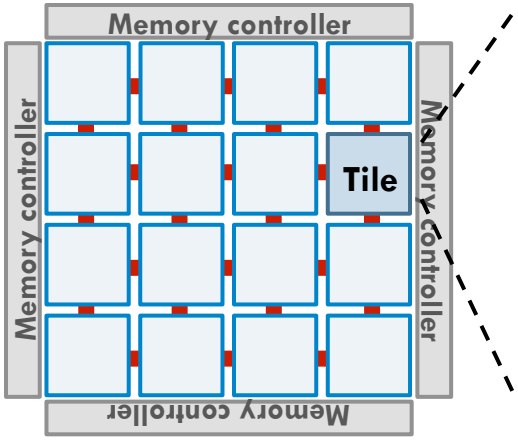
16 MB shared L3 (1MB/tile)
256 KB per-tile L2s
32 KB per-core L1s

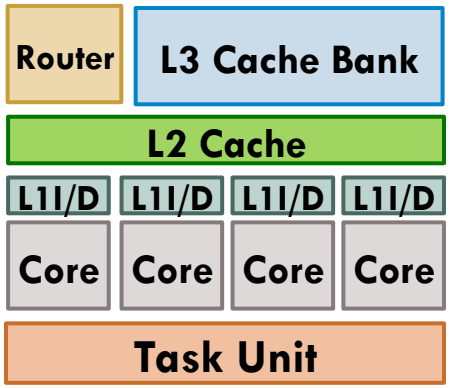
4096 task queue entries (64/core)
1024 commit queue entries (16/core)
256-byte, 8-way Bloom filters

Evaluation Methodology

- Event-driven, sequential, Pin-based simulator

- Target system: 64-core, 16-tile chip



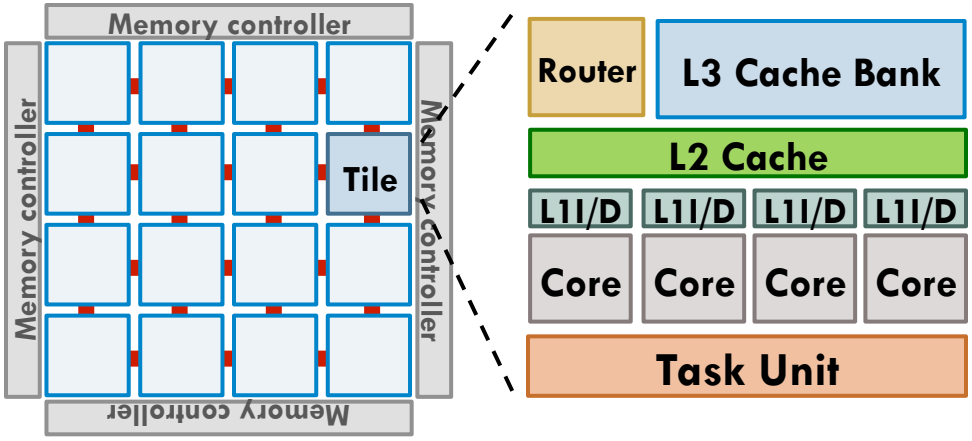


16 MB shared L3 (1MB/tile)
256 KB per-tile L2s
32 KB per-core L1s

4096 task queue entries (64/core)
1024 commit queue entries (16/core)
256-byte, 8-way Bloom filters

Evaluation Methodology

- Event-driven, sequential, Pin-based simulator
- Target system: 64-core, 16-tile chip

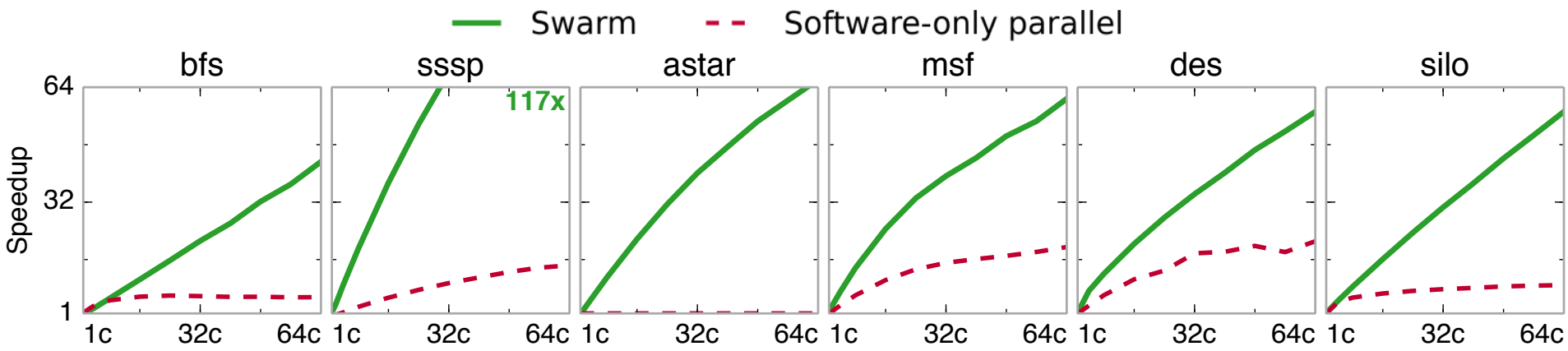


16 MB shared L3 (1MB/tile)
256 KB per-tile L2s
32 KB per-core L1s

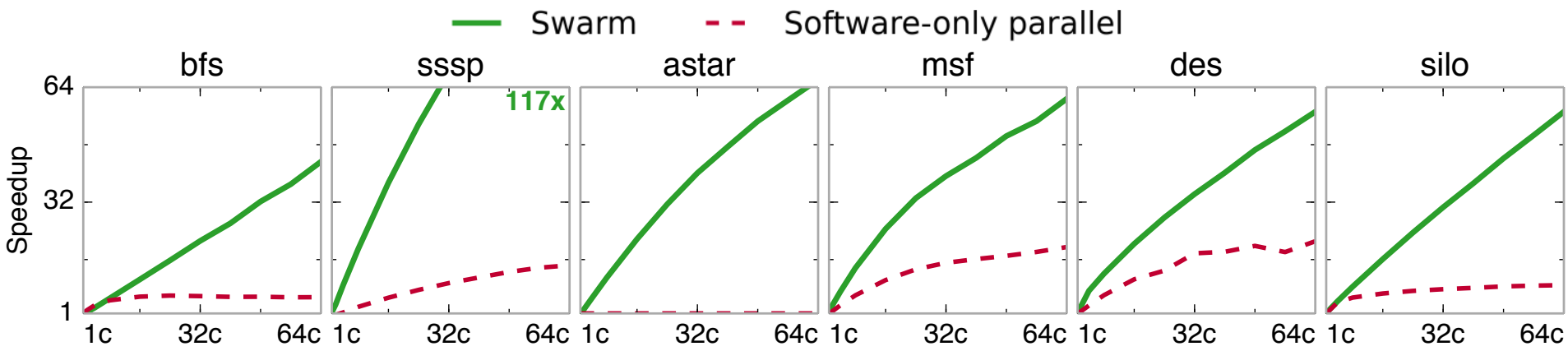
4096 task queue entries (64/core)
1024 commit queue entries (16/core)
256-byte, 8-way Bloom filters

- Scalability experiments from 1-64 cores
  - Scaled-down systems have fewer tiles

Swarm vs. Software Versions

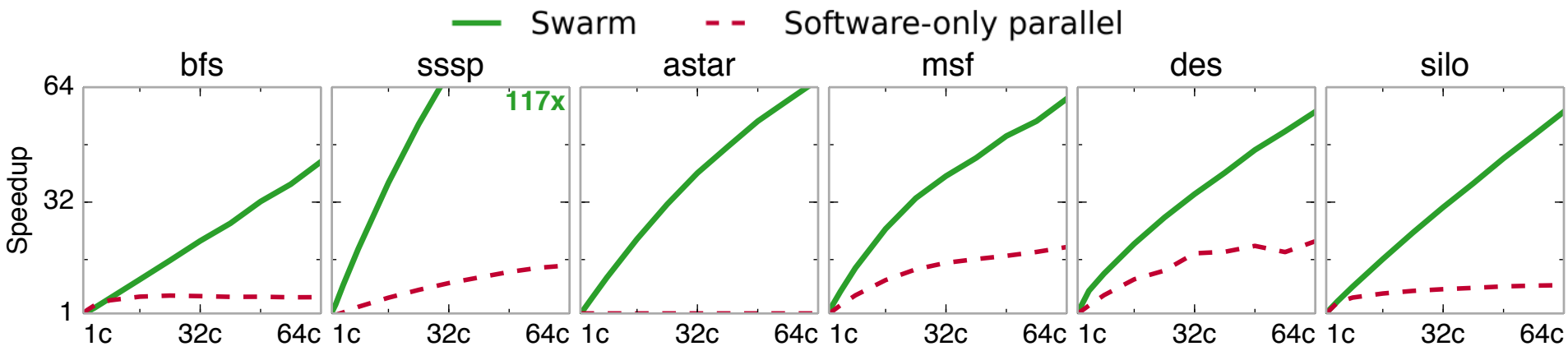


Swarm vs. Software Versions



43x – 117x faster than serial versions

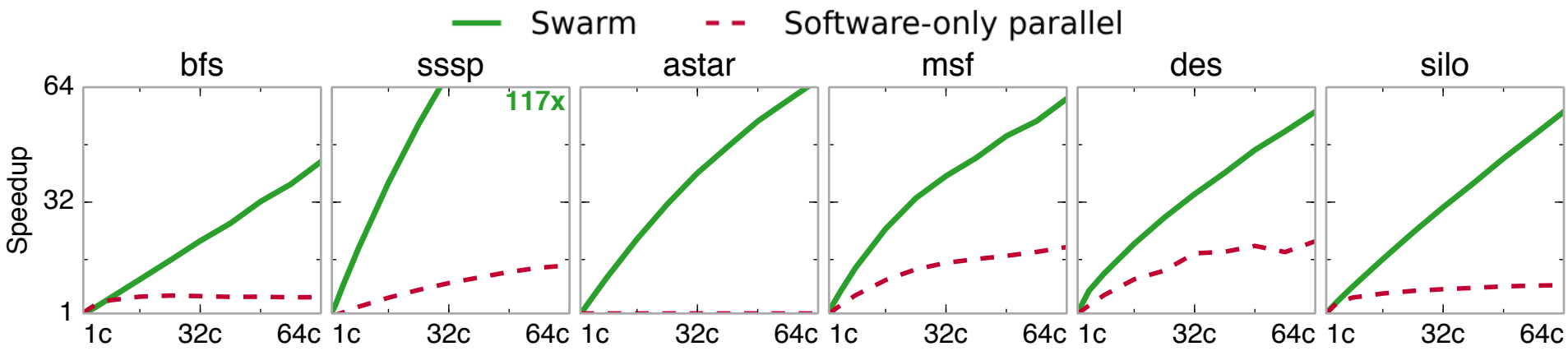
Swarm vs. Software Versions



43x – 117x faster than serial versions

3x – 18x faster than parallel versions

Swarm vs. Software Versions

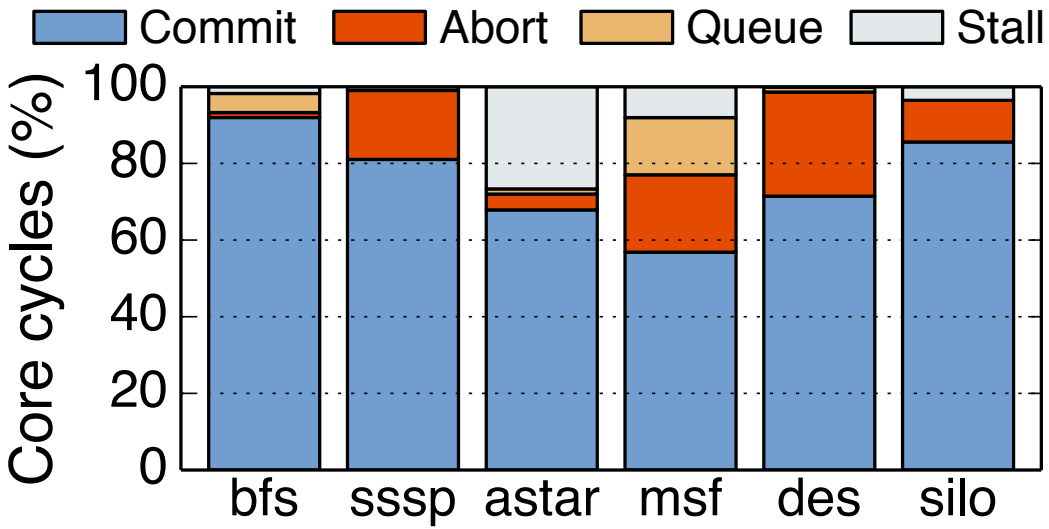


43x – 117x faster than serial versions

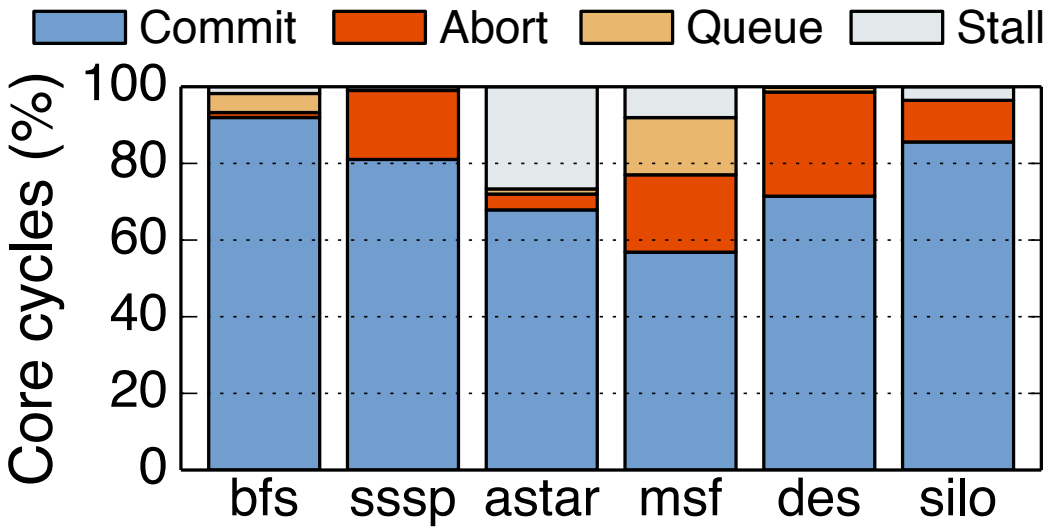
3x – 18x faster than parallel versions

Simple implicitly-parallel code

Swarm Uses Resources Efficiently

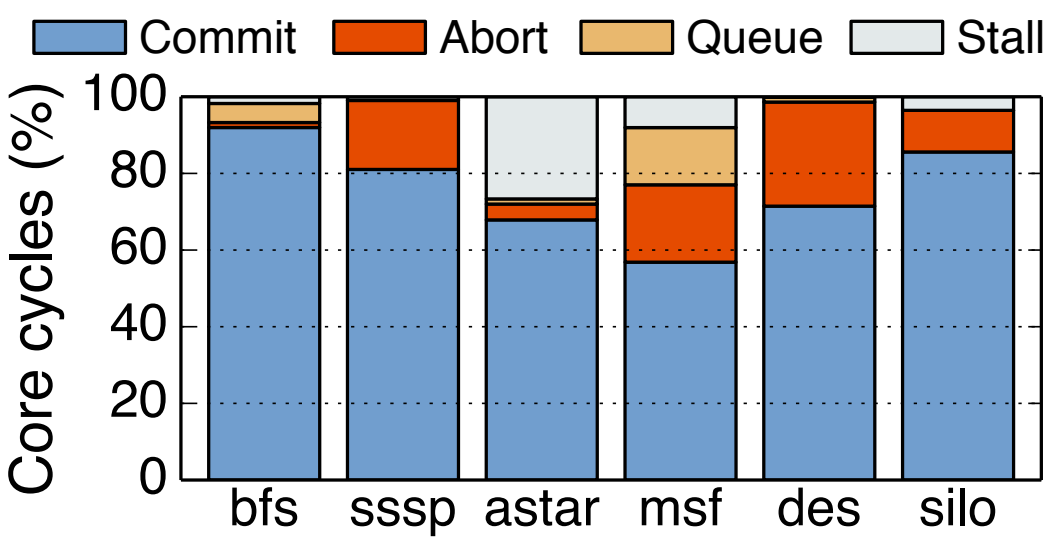


Swarm Uses Resources Efficiently

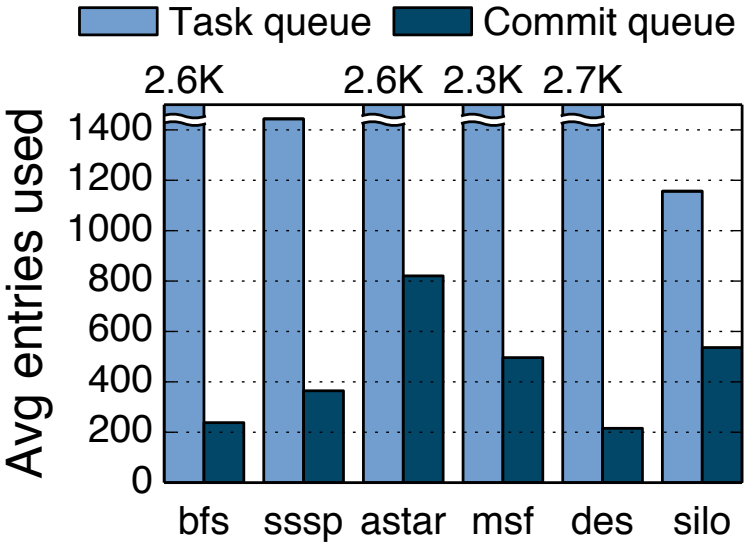


Most time spent executing tasks that commit

Swarm Uses Resources Efficiently

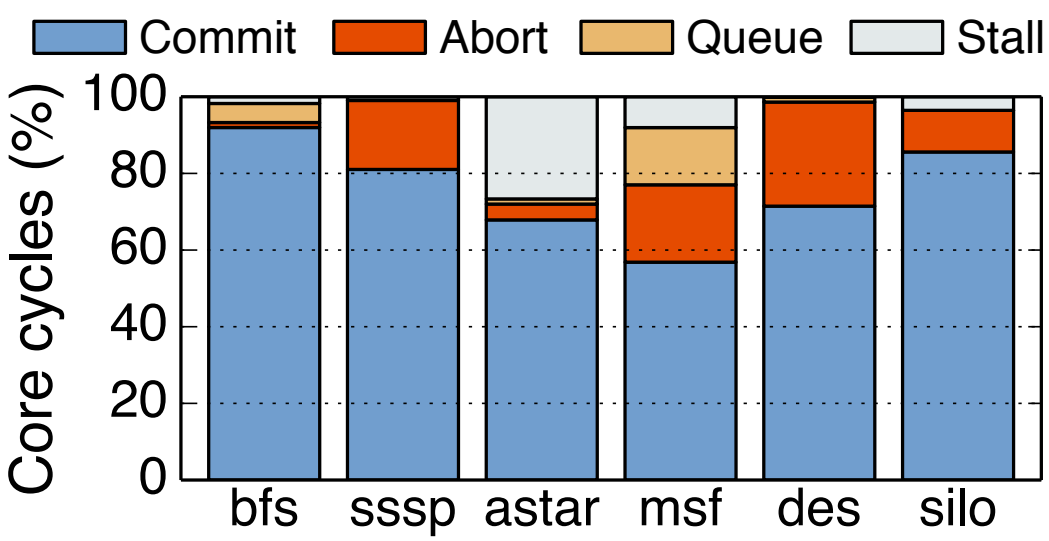


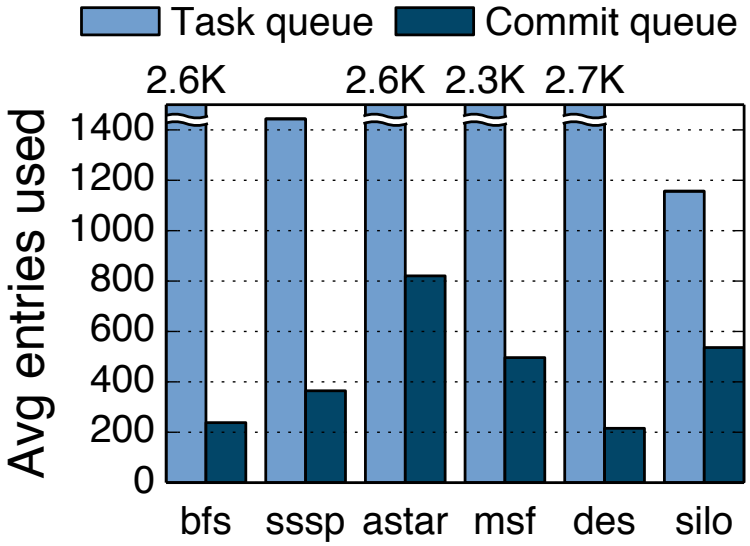
Most time spent executing tasks that commit



Swarm speculates 200-800 tasks ahead on average

Swarm Uses Resources Efficiently





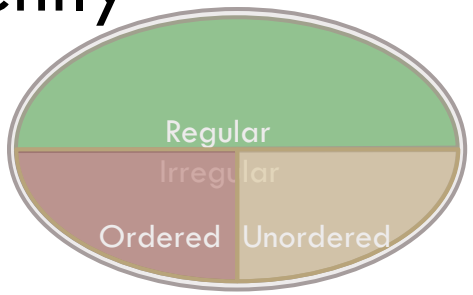
Most time spent executing tasks that commit

Swarm speculates 200-800 tasks ahead on average

- Speculation adds moderate energy overheads:
  - 15% extra network traffic
  - Conflict check logic triggered in 9-16% of cycles

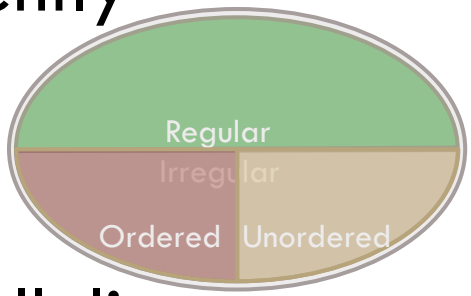
Conclusions

- Swarm exploits ordered parallelism efficiently
  - **Necessary** to parallelize many key algorithms
  - **Simplifies** parallel programming in general



Conclusions

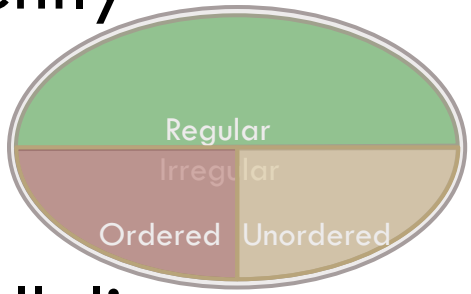
- Swarm exploits ordered parallelism efficiently
  - **Necessary** to parallelize many key algorithms
  - **Simplifies** parallel programming in general



- Conventional wisdom: Ordering limits parallelism

Conclusions

- Swarm exploits ordered parallelism efficiently
  - **Necessary** to parallelize many key algorithms
  - **Simplifies** parallel programming in general



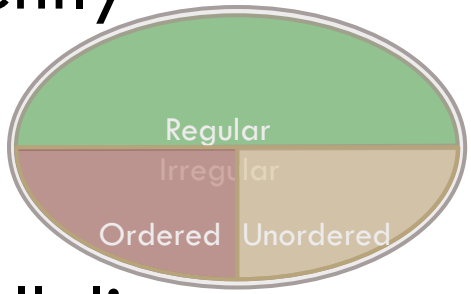
- ~~Conventional wisdom: Ordering limits parallelism~~

  Expressive execution model + large window =

  Only true data dependences limit parallelism

Conclusions

- Swarm exploits ordered parallelism efficiently
  - **Necessary** to parallelize many key algorithms
  - **Simplifies** parallel programming in general



- ~~Conventional wisdom: Ordering limits parallelism~~

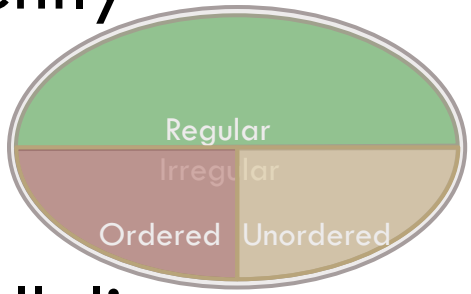
  Expressive execution model + large window =

  Only true data dependences limit parallelism

- Conventional wisdom: Speculation is wasteful

Conclusions

- Swarm exploits ordered parallelism efficiently
  - **Necessary** to parallelize many key algorithms
  - **Simplifies** parallel programming in general



- ~~Conventional wisdom: Ordering limits parallelism~~
  Expressive execution model + large window =
  Only true data dependences limit parallelism
- ~~Conventional wisdom: Speculation is wasteful~~
  Speculation unlocks plentiful ordered parallelism
  Can trade parallelism for efficiency (e.g., simpler cores)

Thanks for your attention!
Questions?

A Scalable Architecture for Ordered Parallelism

Mark Jeffrey, Suvinay Subramanian, Cong Yan,
Joel Emer, Daniel Sanchez

Massachusetts
Institute of
Technology