Kinetic Dependence Graphs

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Keshav Pingali

The University of Texas at Austin

Dependence Graph Scheduling

```
A[N,N] = ...

for i in 1:N
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Application Programmer

Dependence Graph Scheduling

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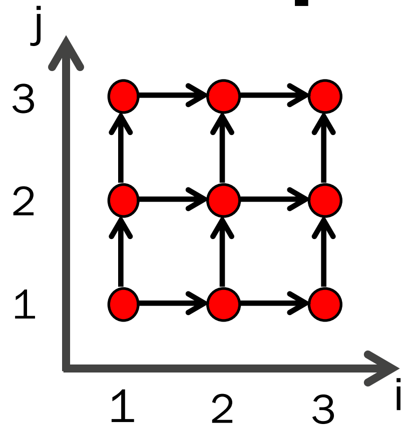
Application Programmer



Compiler

Dependence Graph Scheduling

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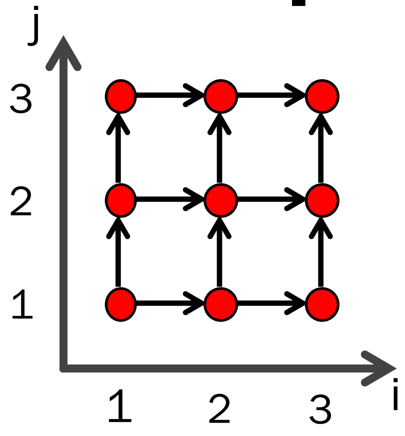

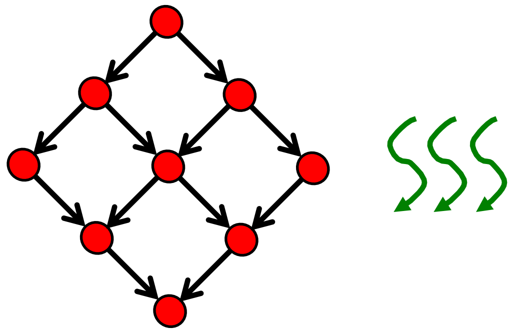

Application Programmer

Compiler

Runtime Scheduler

Dependence Graph Scheduling

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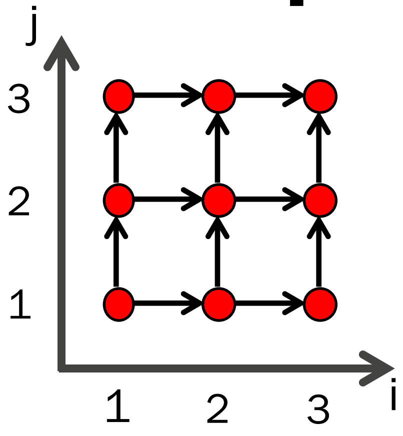

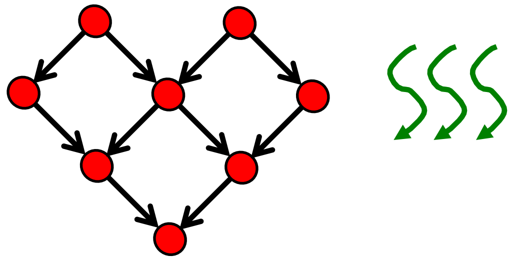

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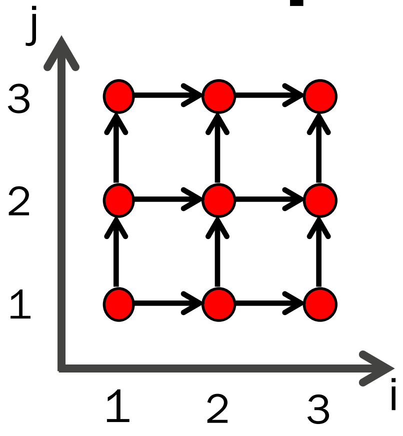

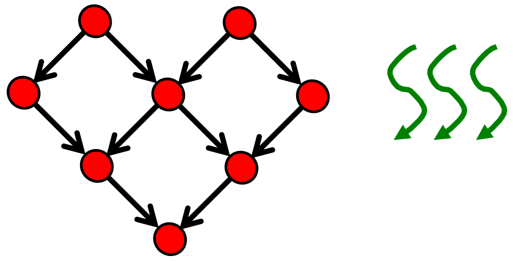

Application Programmer

Compiler
Parallel Task Library

Runtime Scheduler

Dependence Graph Scheduling

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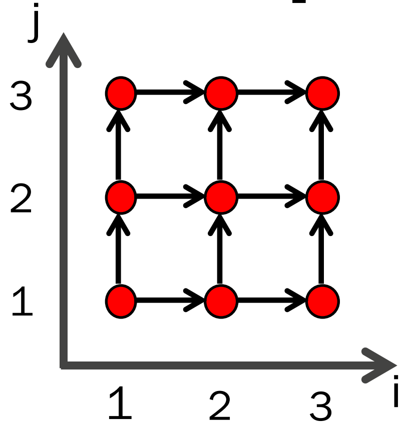

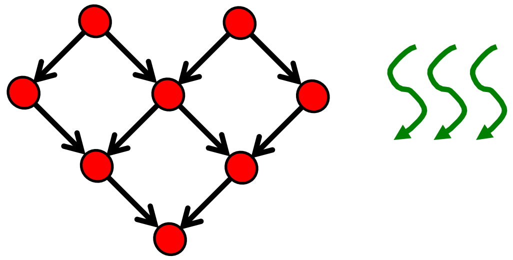

Application Programmer

Compiler
Parallel Task Library
Parallel Programming Model

Runtime Scheduler

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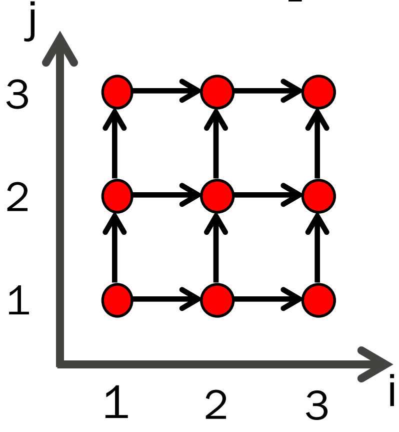

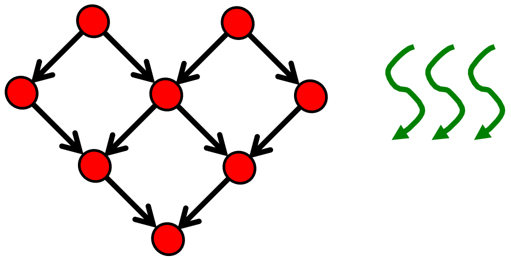

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Runtime Scheduler

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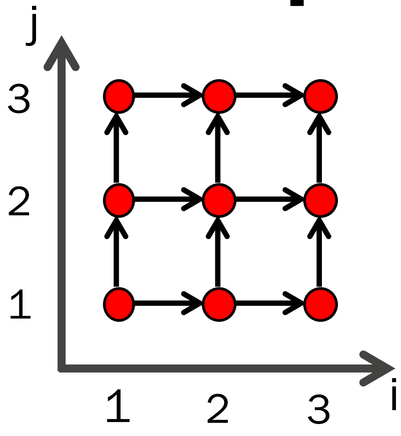

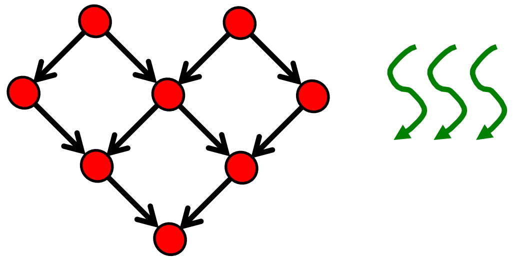

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Runtime Scheduler

σ_0

Dependence Graph Scheduling

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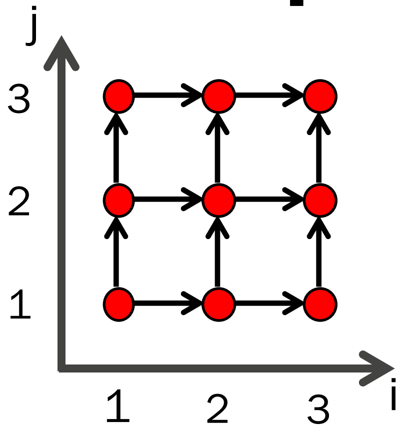

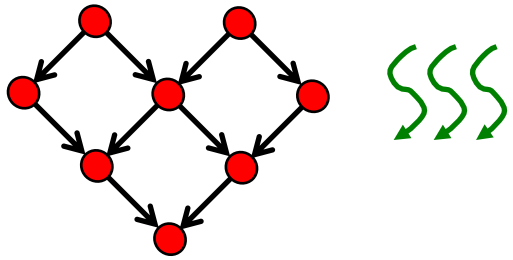

Application Programmer

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Runtime Scheduler

G_0

σ_0

Dependence Graph Scheduling

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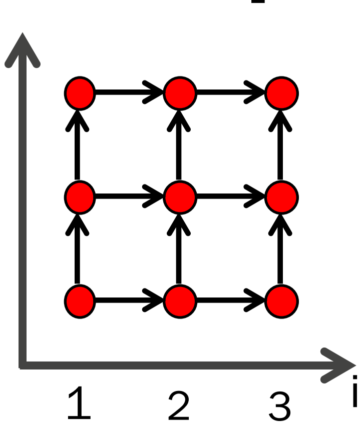

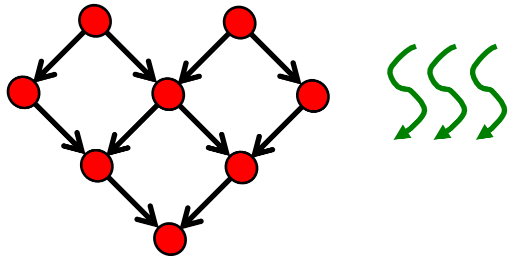

Application Programmer

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Runtime Scheduler

$$\begin{tikzcd} G_0 \arrow[r, Rightarrow, "w_0"] & G_1 \\ \sigma_0 \arrow[u, dashed] & \end{tikzcd}$$

Dependence Graph Scheduling

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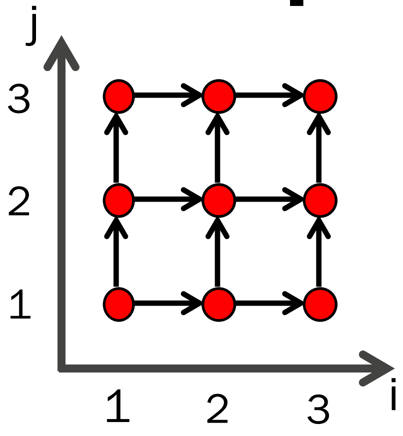

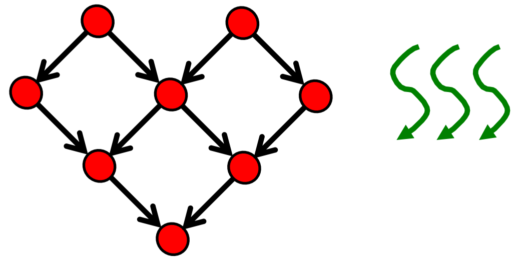

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Runtime Scheduler

Execute in Parallel

$$\begin{tikzcd}
G_0 \arrow[r, Rightarrow, "w_0"] & \boxed{G_1 \arrow[r, Rightarrow, "w_1"] & G_2 \arrow[r, Rightarrow, "w_2"] & {}} \\
\sigma_0 \arrow[u, dashed]
\end{tikzcd}$$

Dependence Graph Scheduling

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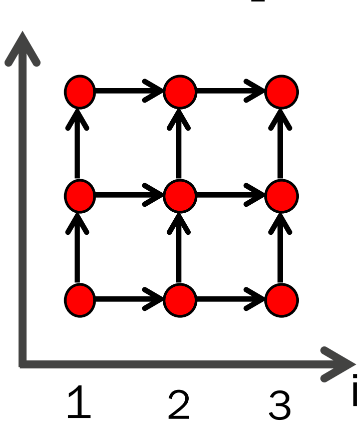

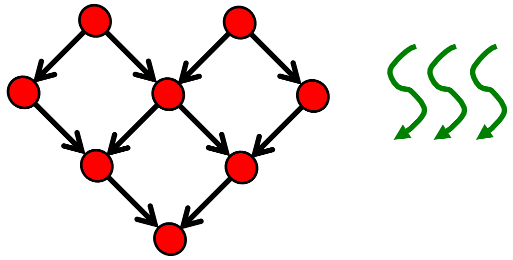

Application Programmer

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Runtime Scheduler

$$\begin{tikzcd} G_0 \arrow[r, Rightarrow, "w_0"] & G_1 \arrow[r, Rightarrow, "w_1"] & G_2 \arrow[r, Rightarrow, "w_2"] & \ldots \arrow[r, Rightarrow, "w_{n-1}"] & G_n \\ \sigma_0 \arrow[u, dashed] \end{tikzcd}$$

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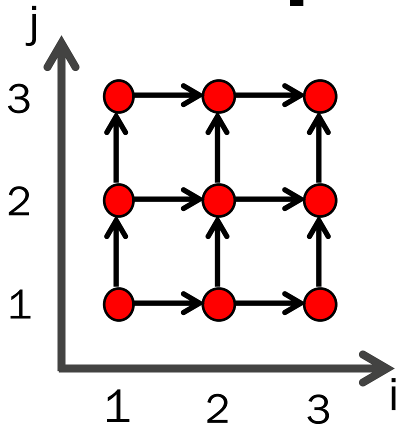

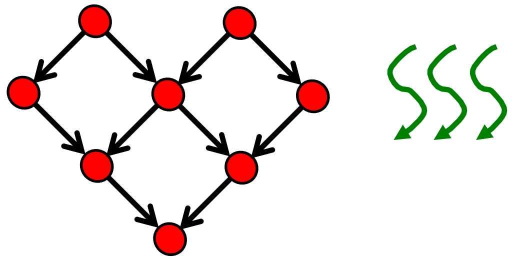

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Runtime Scheduler

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G_0 \arrow[r, Rightarrow, "w_0"] & G_1 \arrow[r, Rightarrow, "w_1"] & G_2 \arrow[r, Rightarrow, "w_2"] & \dots \arrow[r, Rightarrow, "w_{n-1}"] & G_n \\
\sigma_0 \arrow[u, dashed] \arrow[r, "w_0"] & \sigma_1 \arrow[u, dashed] & & &
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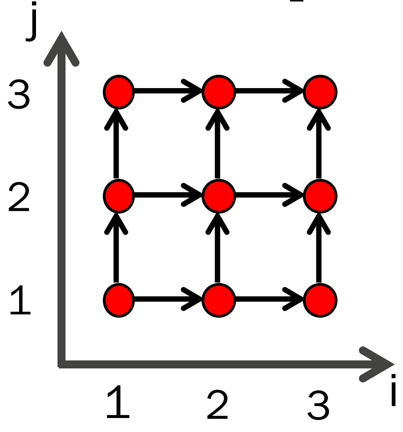

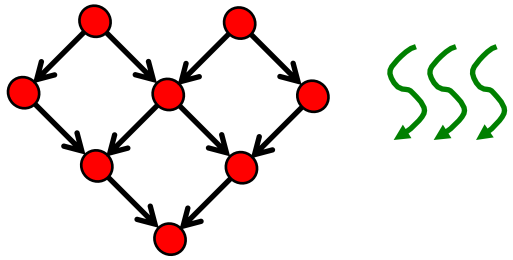

Application Programmer

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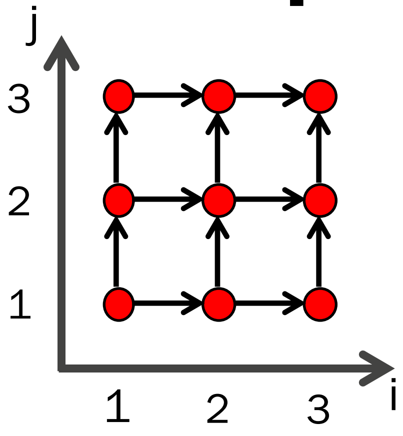
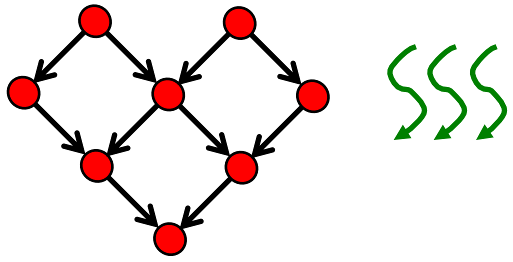




Application Programmer

Compiler
Parallel Task Library
Parallel Programming Model
⋮

Runtime Scheduler

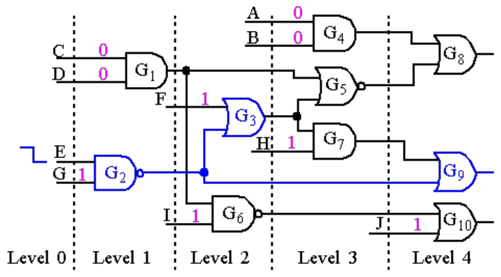
Scheduler World

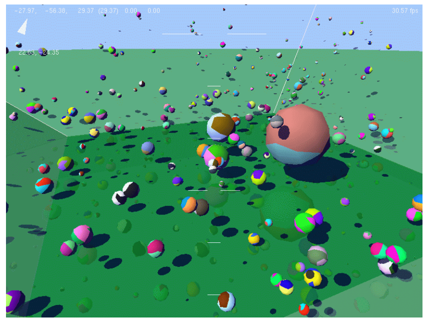
Program World

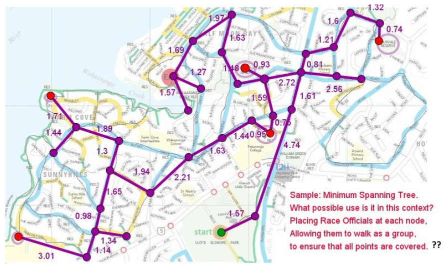
$$\begin{tikzcd} G_0 \arrow[r, Rightarrow, "w_0"] & G_1 \arrow[r, Rightarrow, "w_1"] & G_2 \arrow[r, Rightarrow, "w_2"] & \dots \arrow[r, Rightarrow, "w_{n-1}"] & G_n \\ \sigma_0 \arrow[r, "w_0"] \arrow[u, dashed] & \sigma_1 \arrow[r, "w_1"] \arrow[u, dashed] & \sigma_2 \arrow[r, "w_2"] \arrow[u, dashed] & \dots \arrow[r, "w_{n-1}"] & \sigma_n \arrow[u, dashed] \end{tikzcd}$$

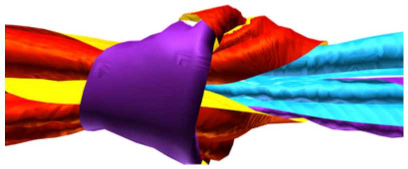
Limitations of Dependence Graphs

- Not always sufficient
  - Discrete event simulation
  - Billiard ball simulation
  - Kruskal’s algorithm for MSTs
  - Asynchronous Variational Integrators
  - …
- Ordered algorithms
  - Have tasks with algorithm-specific order in which tasks must appear to execute
- Can use speculation
  - But overheads can be high for ordered algorithms

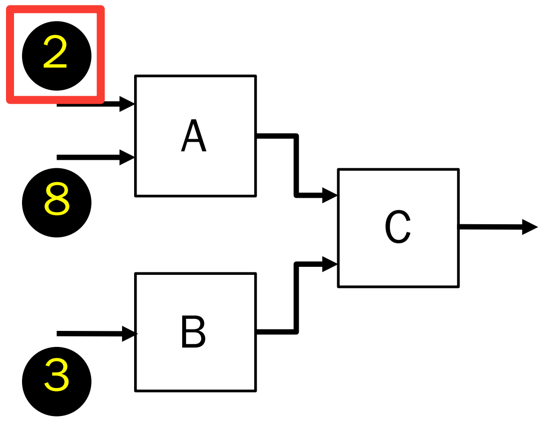





Sample: Minimum Spanning Tree.
What possible use is it in this context?
Placing Race Officials at each node,
Allowing them to walk as a group,
to ensure that all points are covered. ??



Discrete Event Simulation



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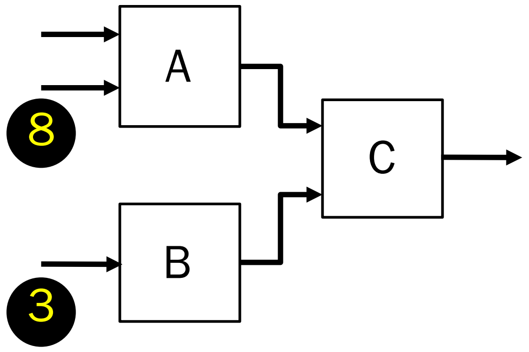

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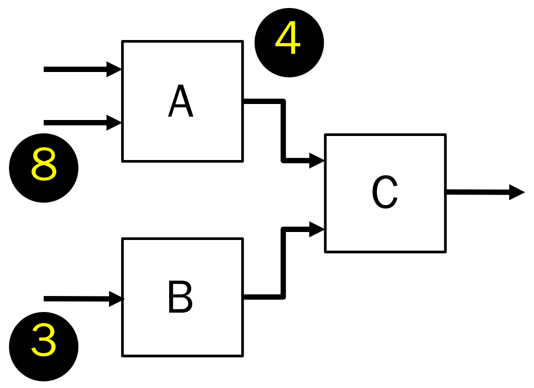

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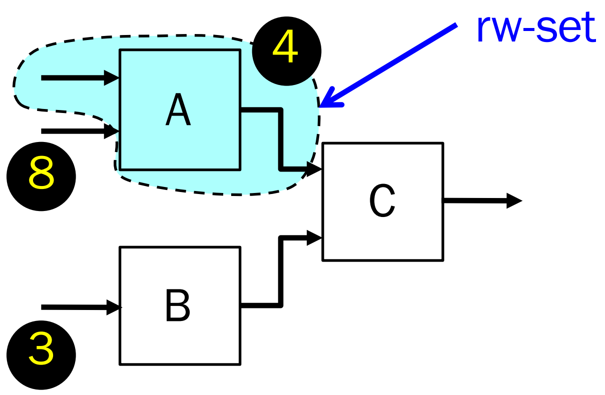

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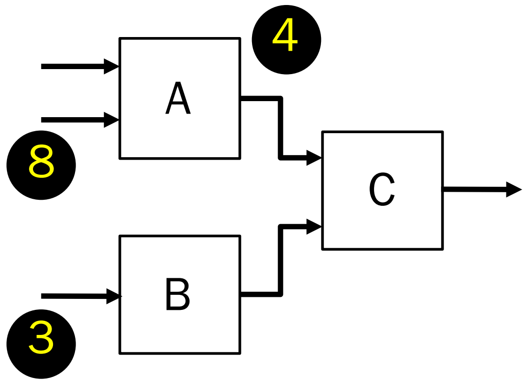

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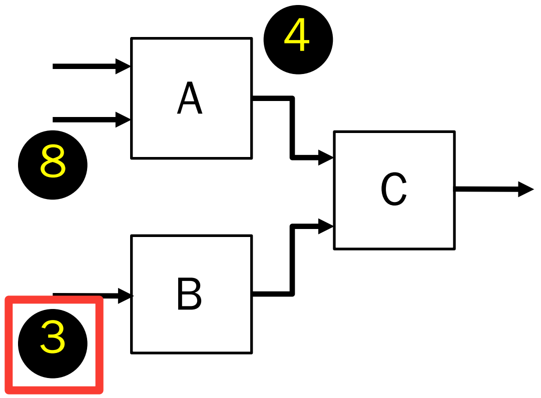

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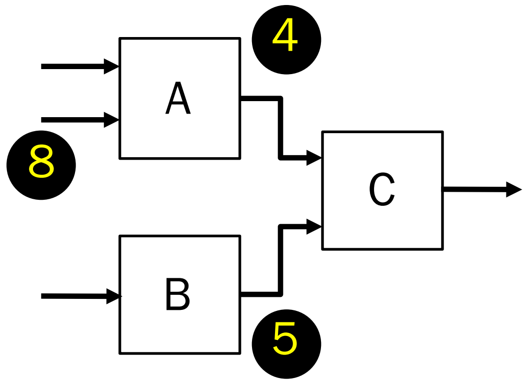

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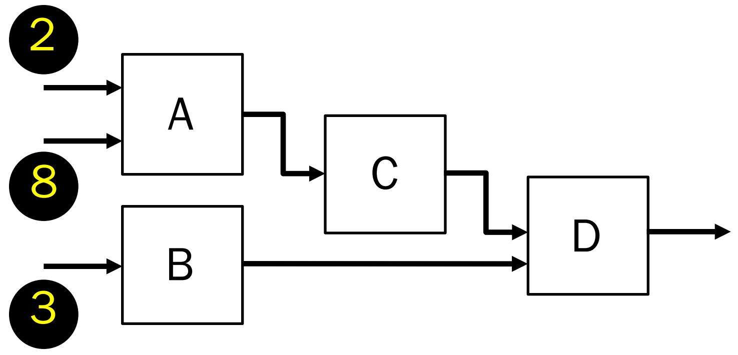

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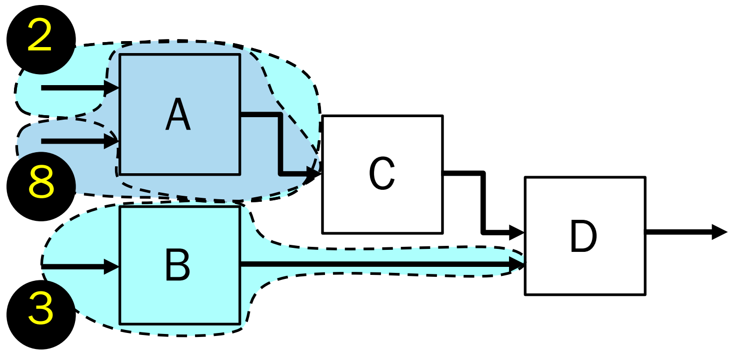

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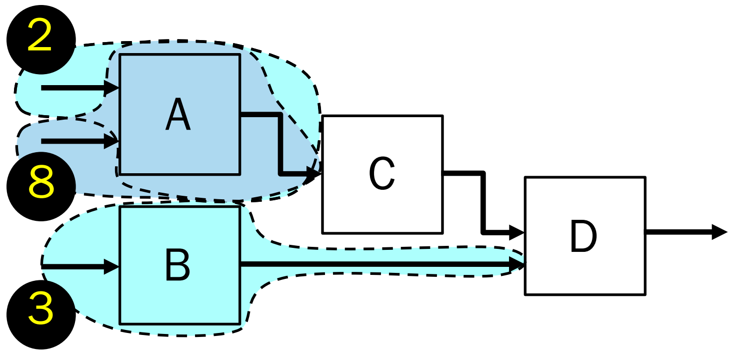
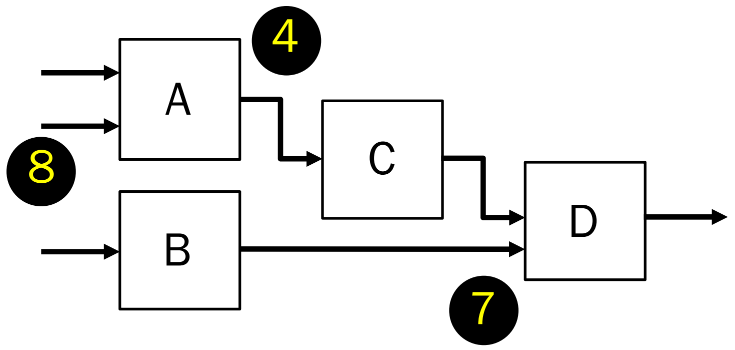
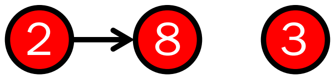


$$\begin{tikzcd} 2 \arrow[r] & 8 & 3 \end{tikzcd}$$

Discrete Event Simulation





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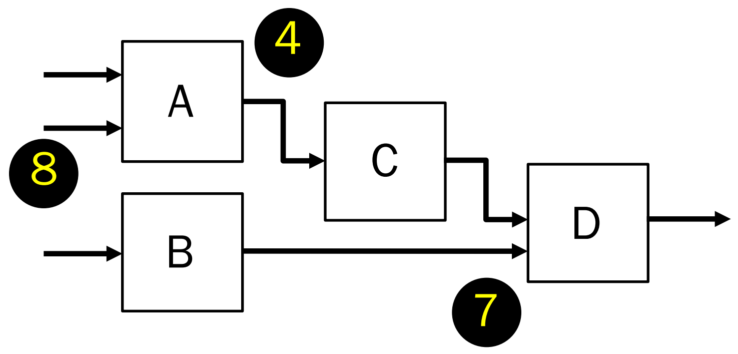

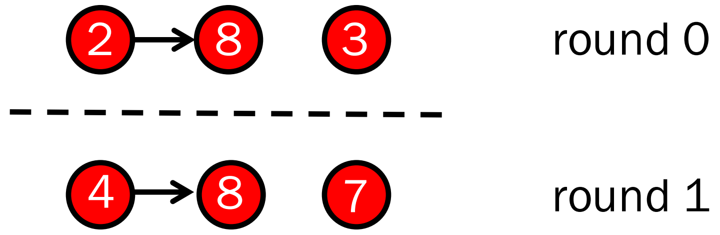

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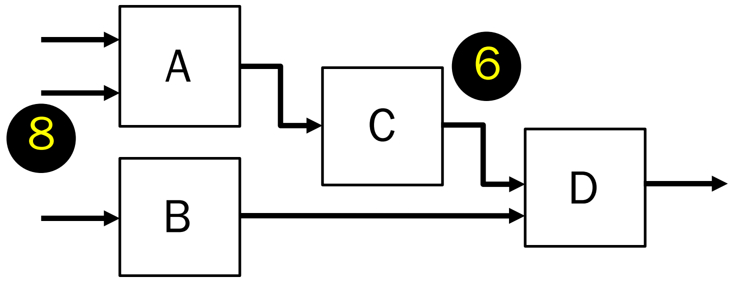

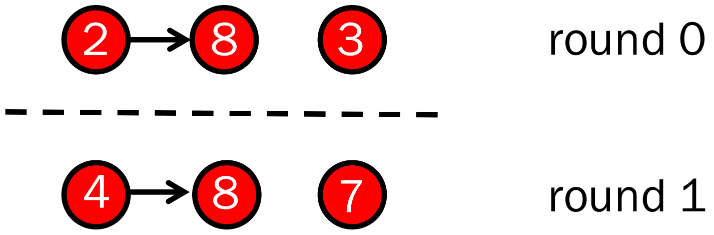

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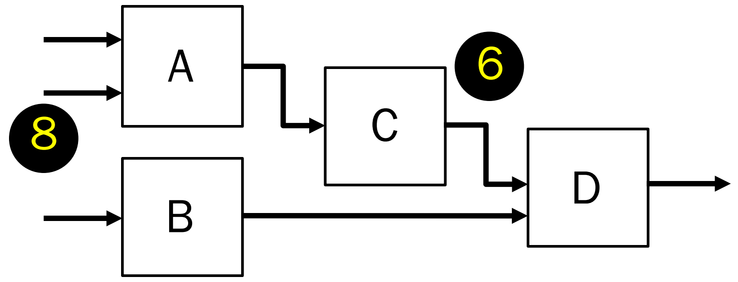

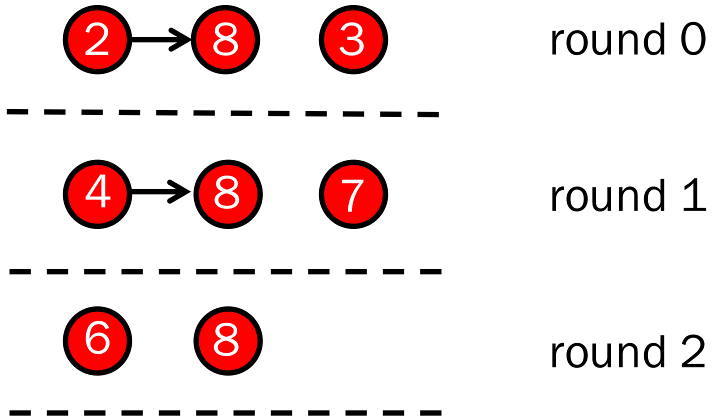

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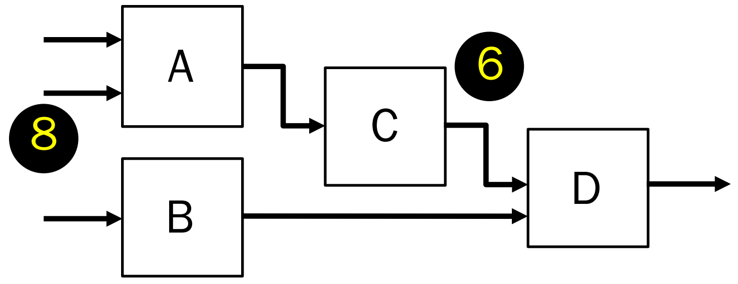

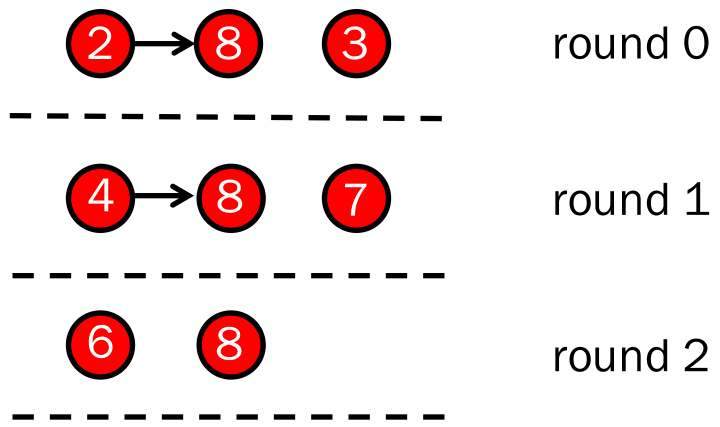

- Inadequacy of dependence graphs
  - Tasks are created dynamically
  - Not all sources are safe to execute
  - Task execution may require updating DAG

Dependence Graph

- A dependence graph is:
  - A DAG ***G*** for the program state ***σ***
  - An update rule ***U*** to produce the next ***G*** after executing task ***w***
    - Remove source

Execute sources

Dependence Graph

$$\begin{tikzcd}
G_0 \arrow[r, Rightarrow, "w_0"] & G_1 \arrow[r, Rightarrow, "w_1"] & G_2 \arrow[r, Rightarrow, "w_2"] & \ldots \arrow[r, Rightarrow, "w_{n-1}"] & G_n \\
\sigma_0 \arrow[u, dashed] \arrow[r, "w_0"] & \sigma_1 \arrow[u, dashed] \arrow[r, "w_1"] & \sigma_2 \arrow[u, dashed] \arrow[r, "w_2"] & \ldots \arrow[r, "w_{n-1}"] & \sigma_n \arrow[u, dashed]
\end{tikzcd}$$

Kinetic Dependence Graph

- A kinetic dependence graph is:
  - A DAG ***G*** for the program state ***σ***
  - A safe-source test ***P***
  - An update rule ***U*** to produce the next ***G*** after executing task ***w***
    - Remove source, update other tasks' dependencies, …

Execute sources

Dependence Graph

$$\begin{tikzcd}
G_0 \arrow[r, Rightarrow, "w_0"] & G_1 \arrow[r, Rightarrow, "w_1"] & G_2 \arrow[r, Rightarrow, "w_2"] & \ldots \arrow[r, Rightarrow, "w_{n-1}"] & G_n \\
\sigma_0 \arrow[u, dashed] \arrow[r, "w_0"] & \sigma_1 \arrow[u, dashed] \arrow[r, "w_1"] & \sigma_2 \arrow[u, dashed] \arrow[r, "w_2"] & \ldots \arrow[r, "w_{n-1}"] & \sigma_n \arrow[u, dashed]
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Kinetic Dependence Graph

- A kinetic dependence graph is:
  - A DAG ***G*** for the program state ***σ***
  - A safe-source test ***P***
  - An update rule ***U*** to produce the next ***G*** after executing task ***w***
    - Remove source, update other tasks’ dependencies, …

Kinetic Dependence Graph

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Execute safe sources

Kinetic Dependence Graph

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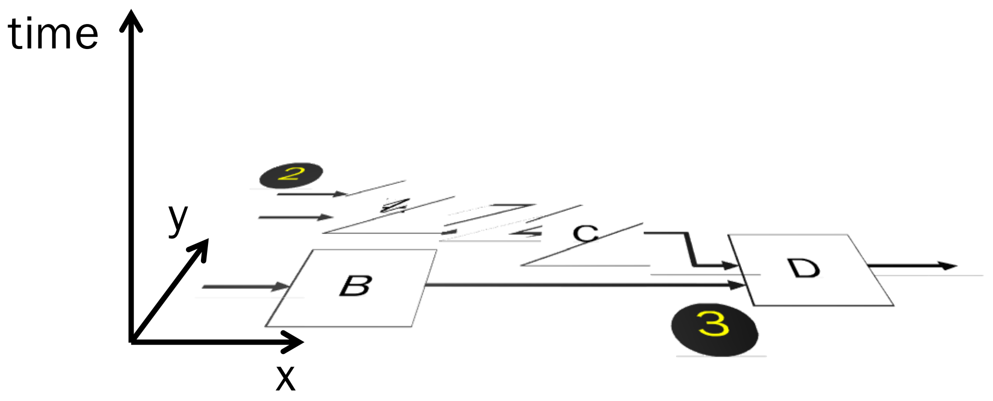
\end{tikzcd}$$

Safe Sources

- Application-specific cone of influence



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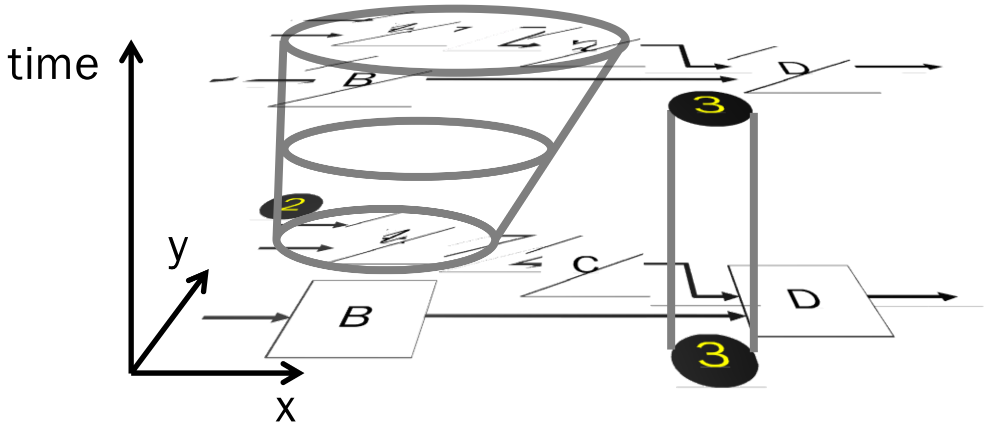

Safe Sources

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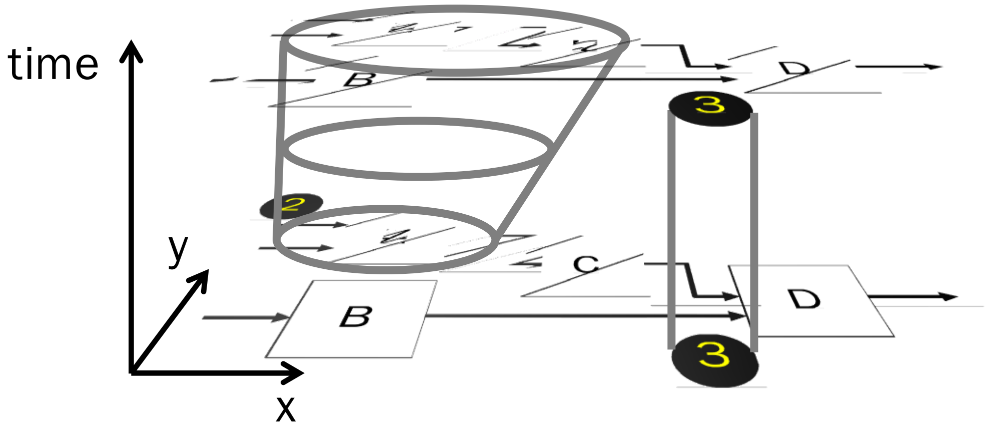
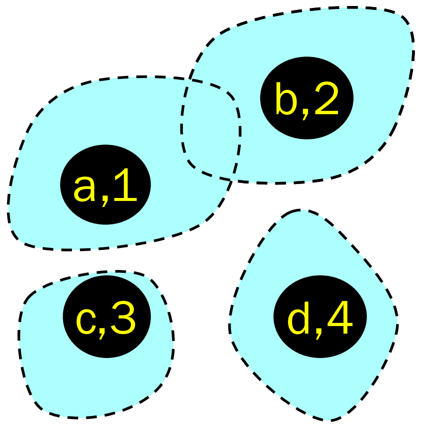


- In some algorithms, all sources are safe
  - Stable source algorithm

General KDG Executor



General KDG Executor

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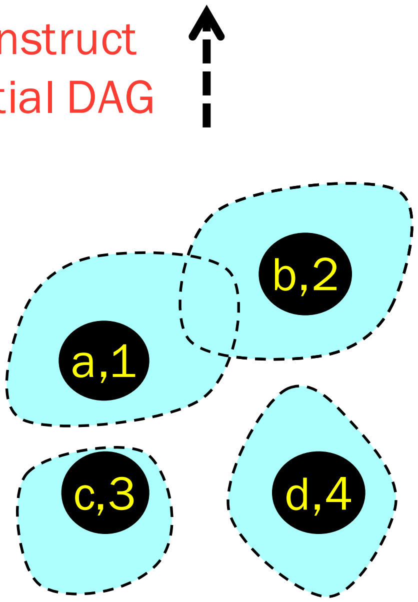

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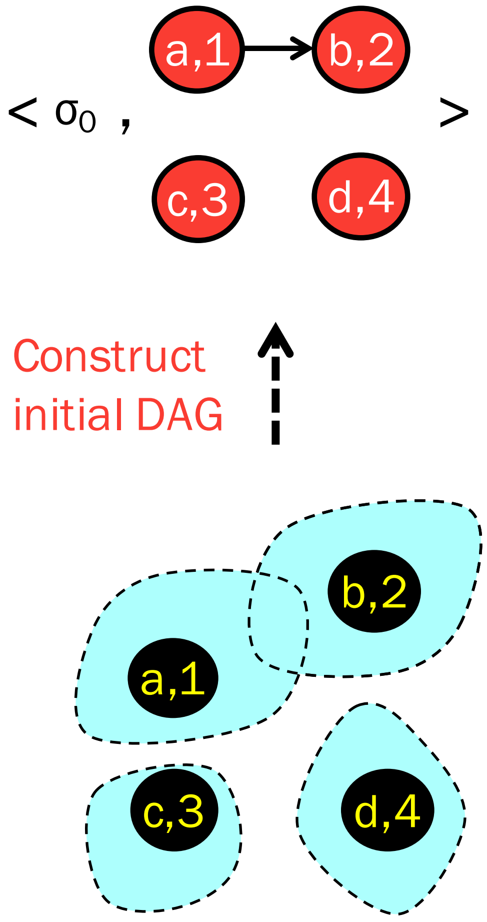

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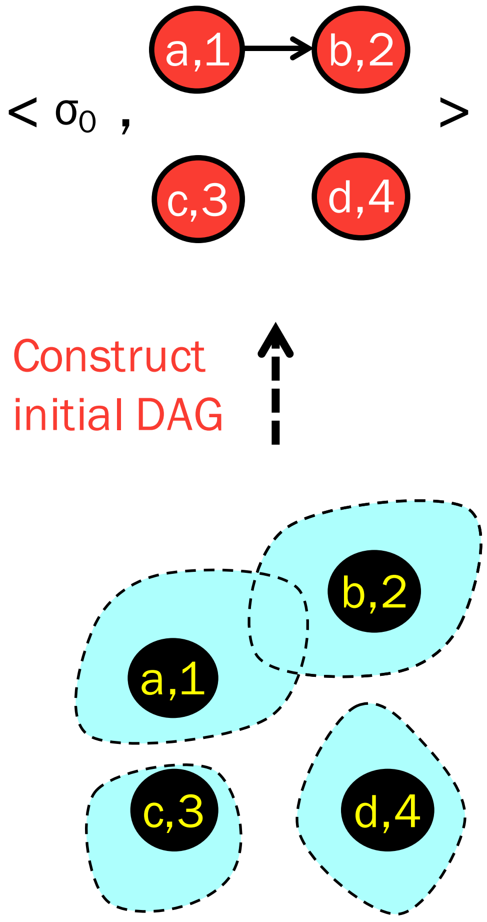

1. Construct initial DAG

2. Apply safe source test
3. Execute
4. Update rw-sets
5. Add new tasks

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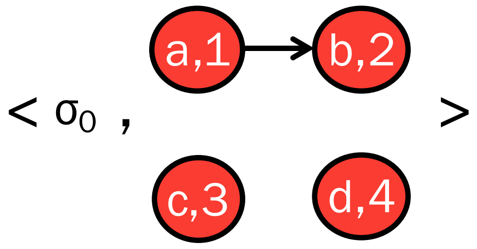

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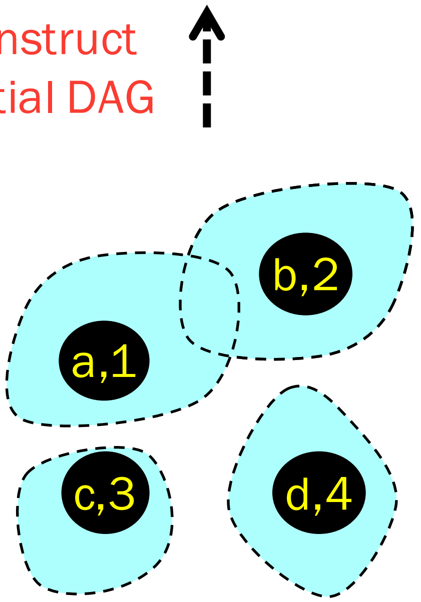

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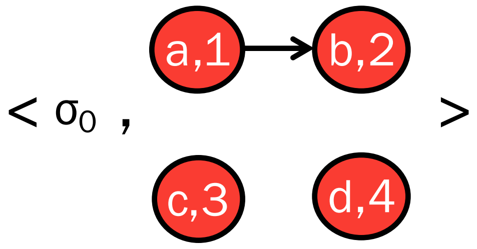

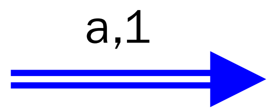

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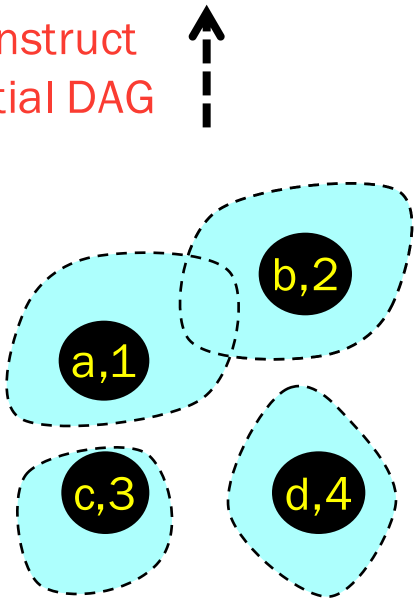

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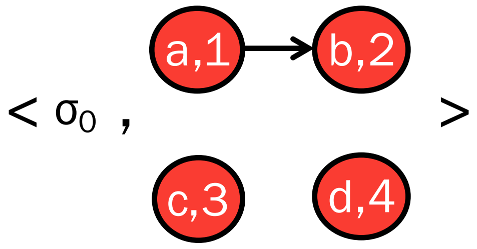

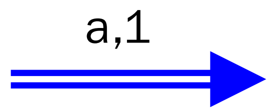

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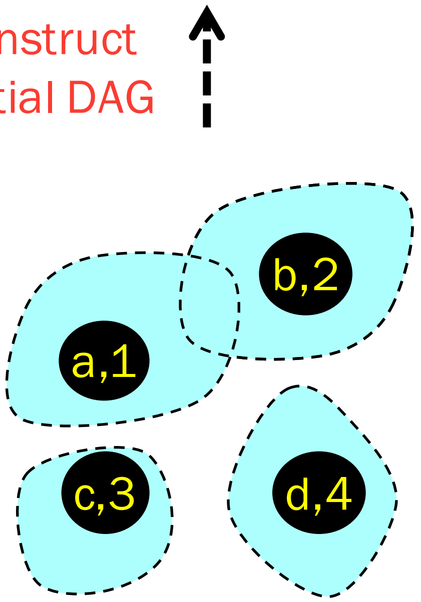

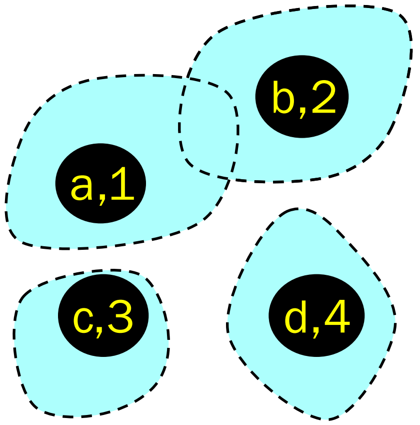

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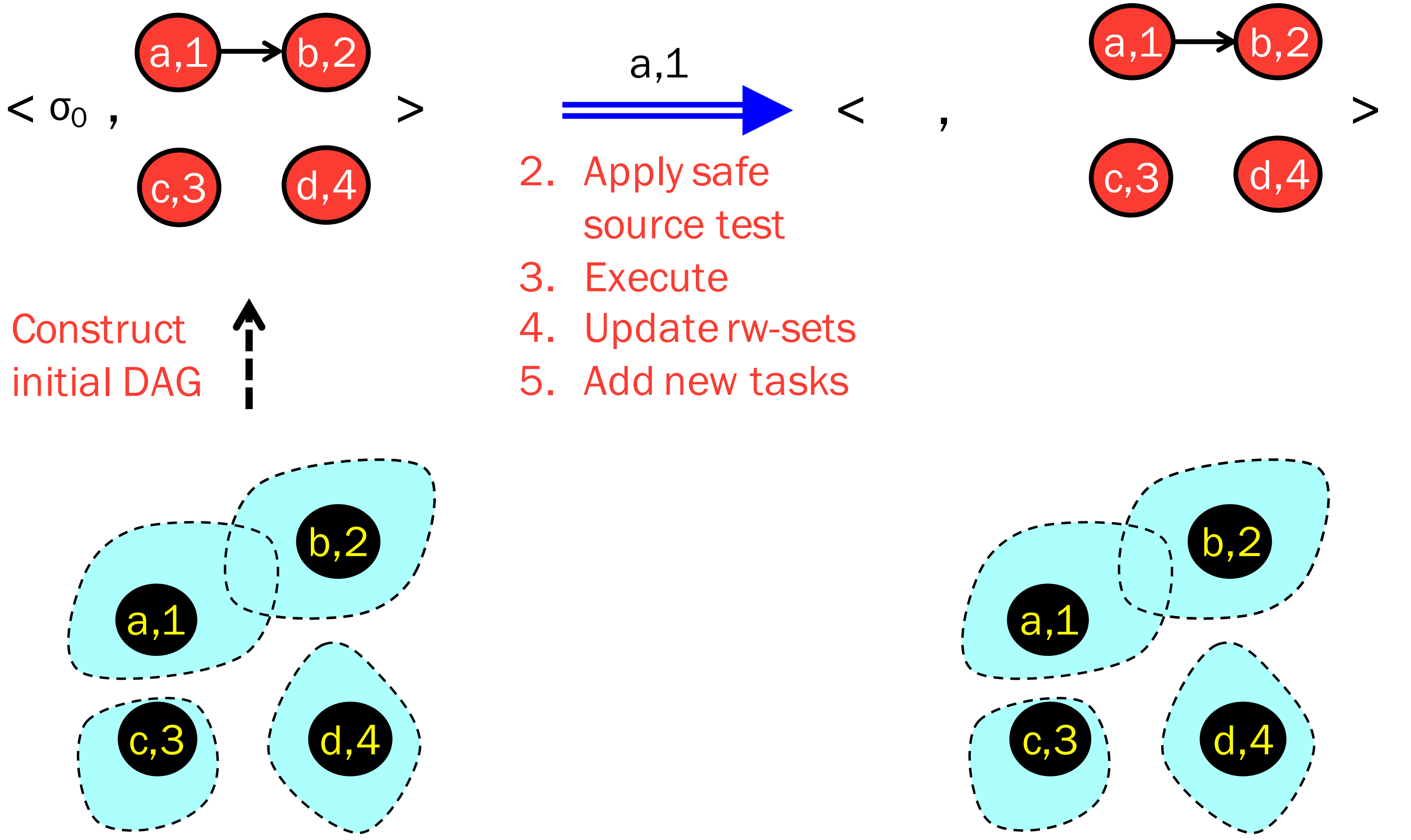

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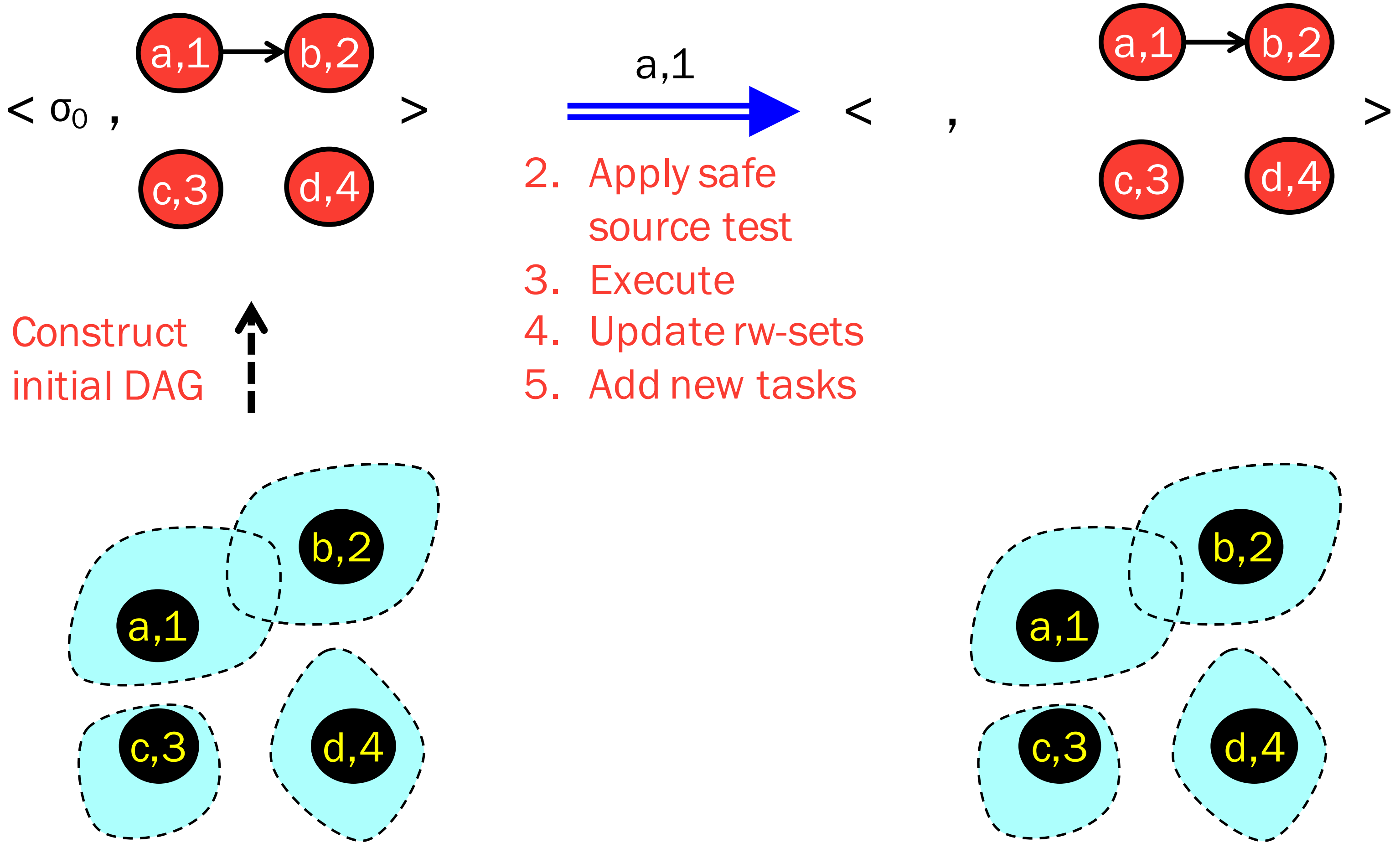

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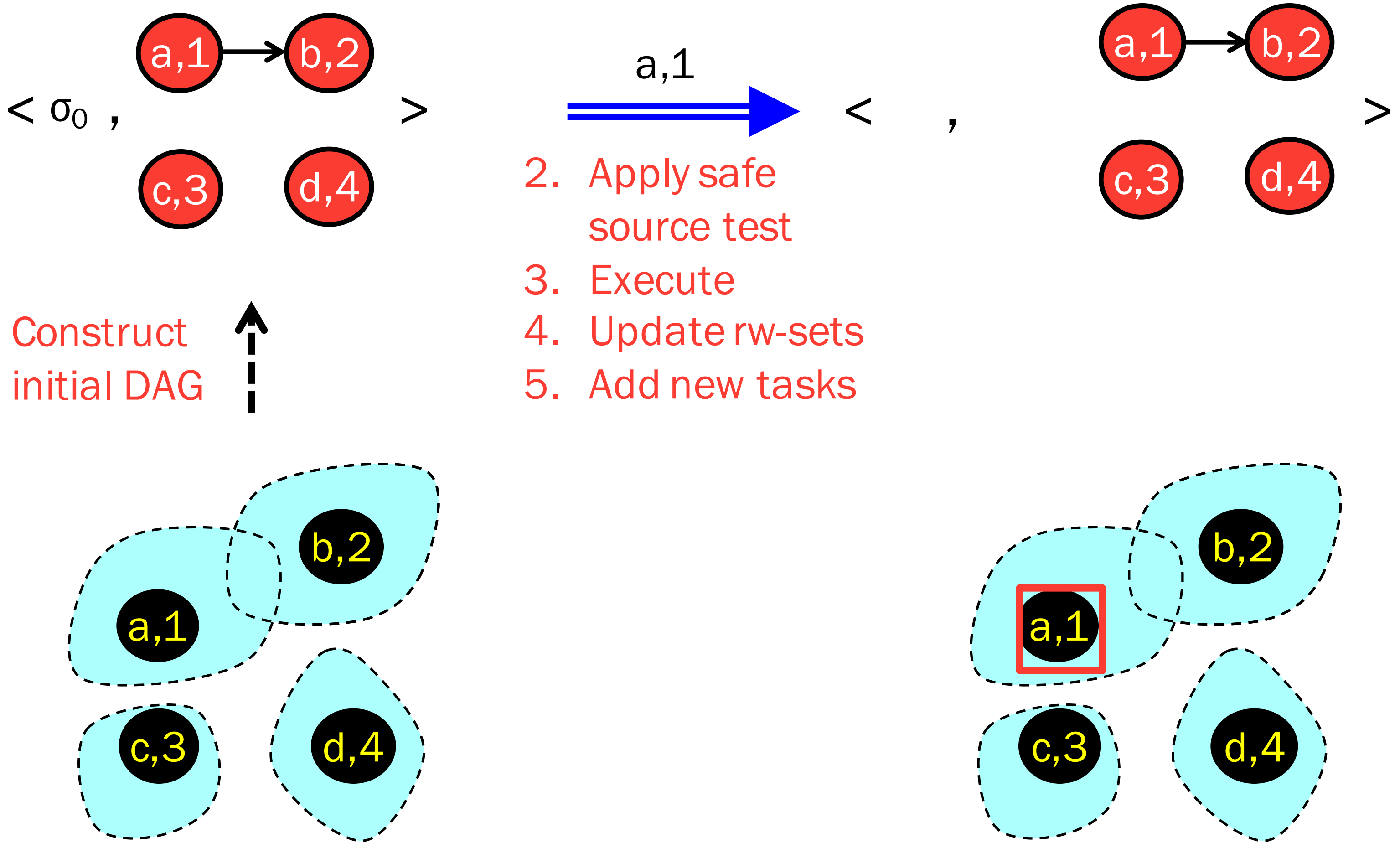

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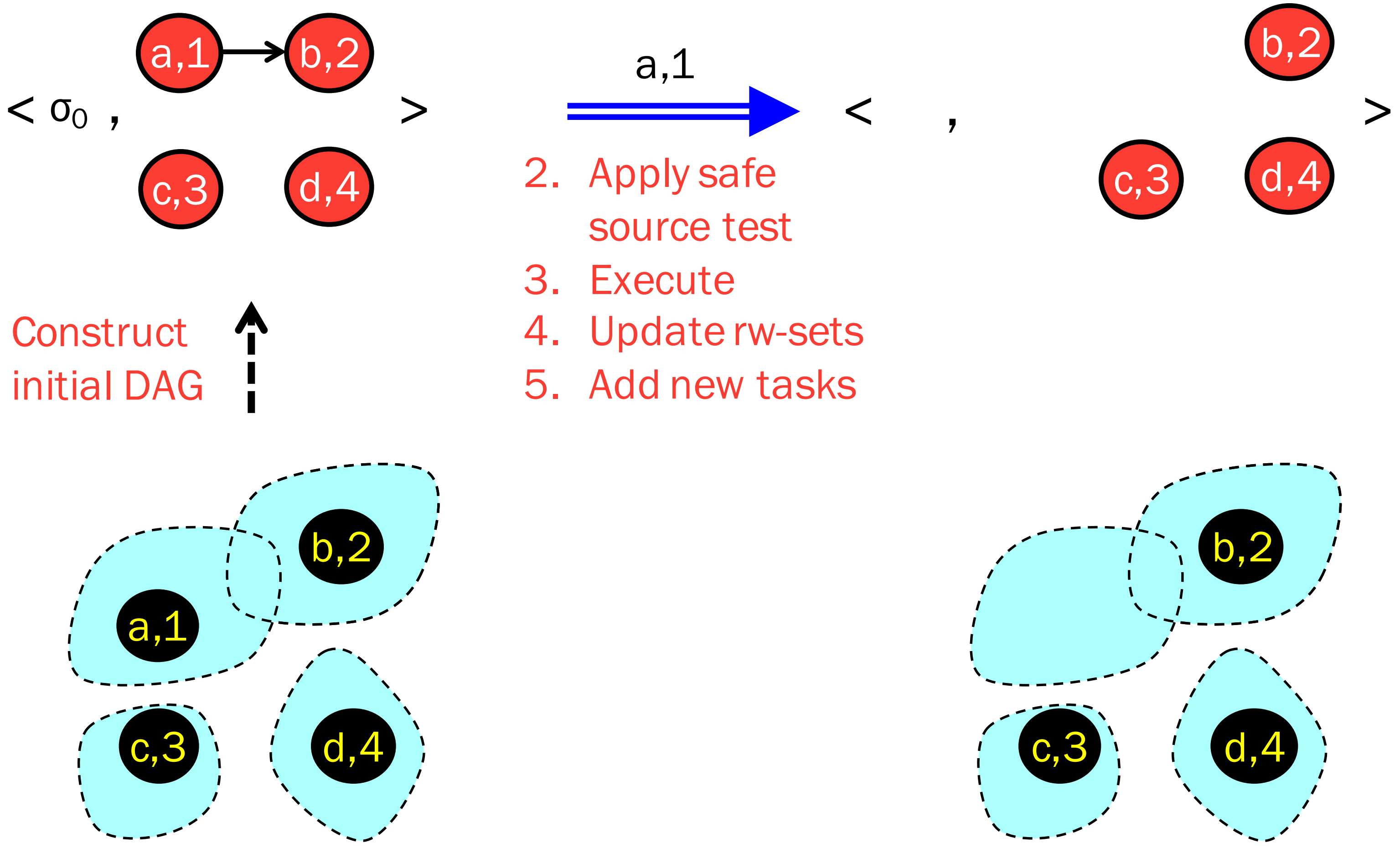

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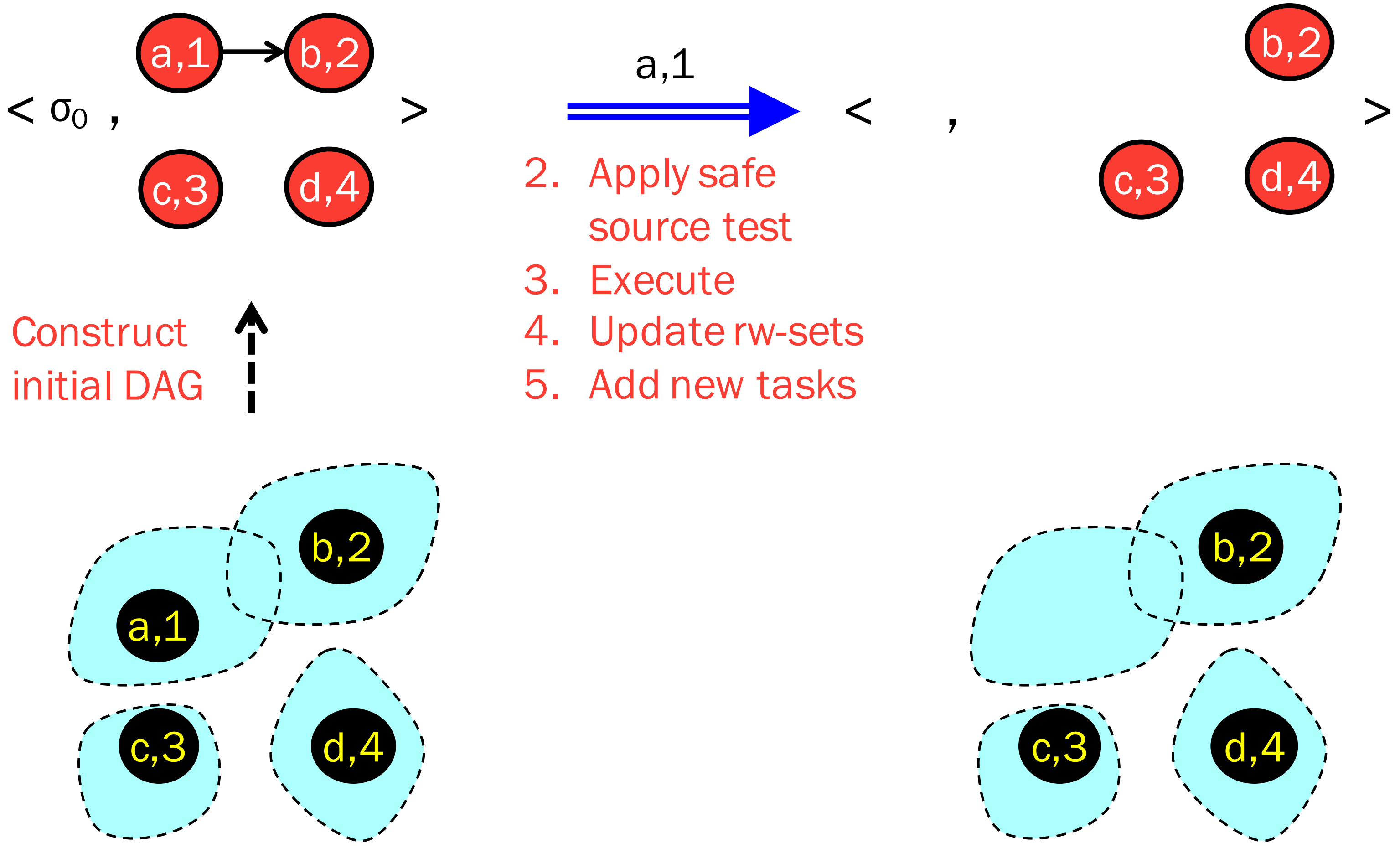

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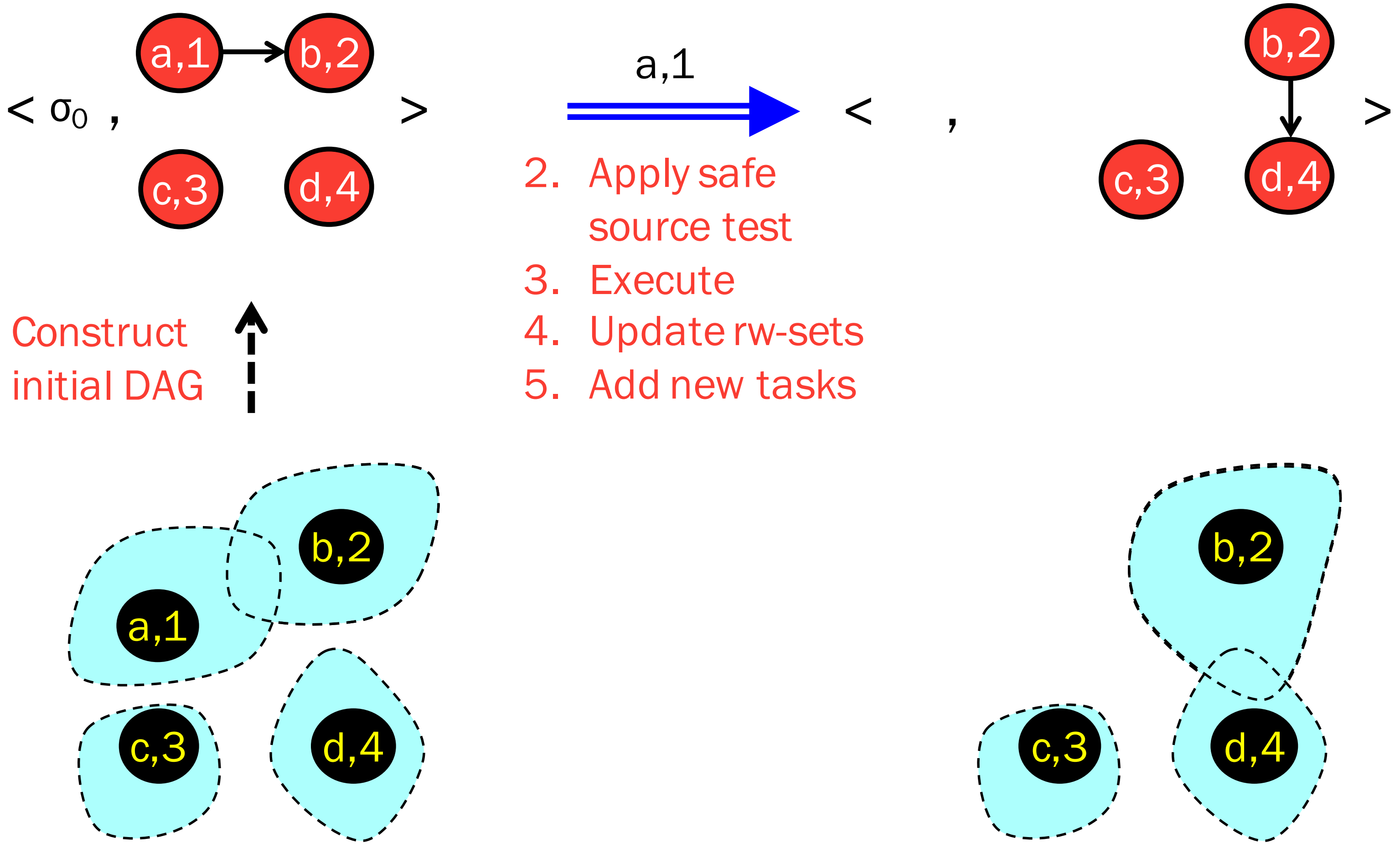

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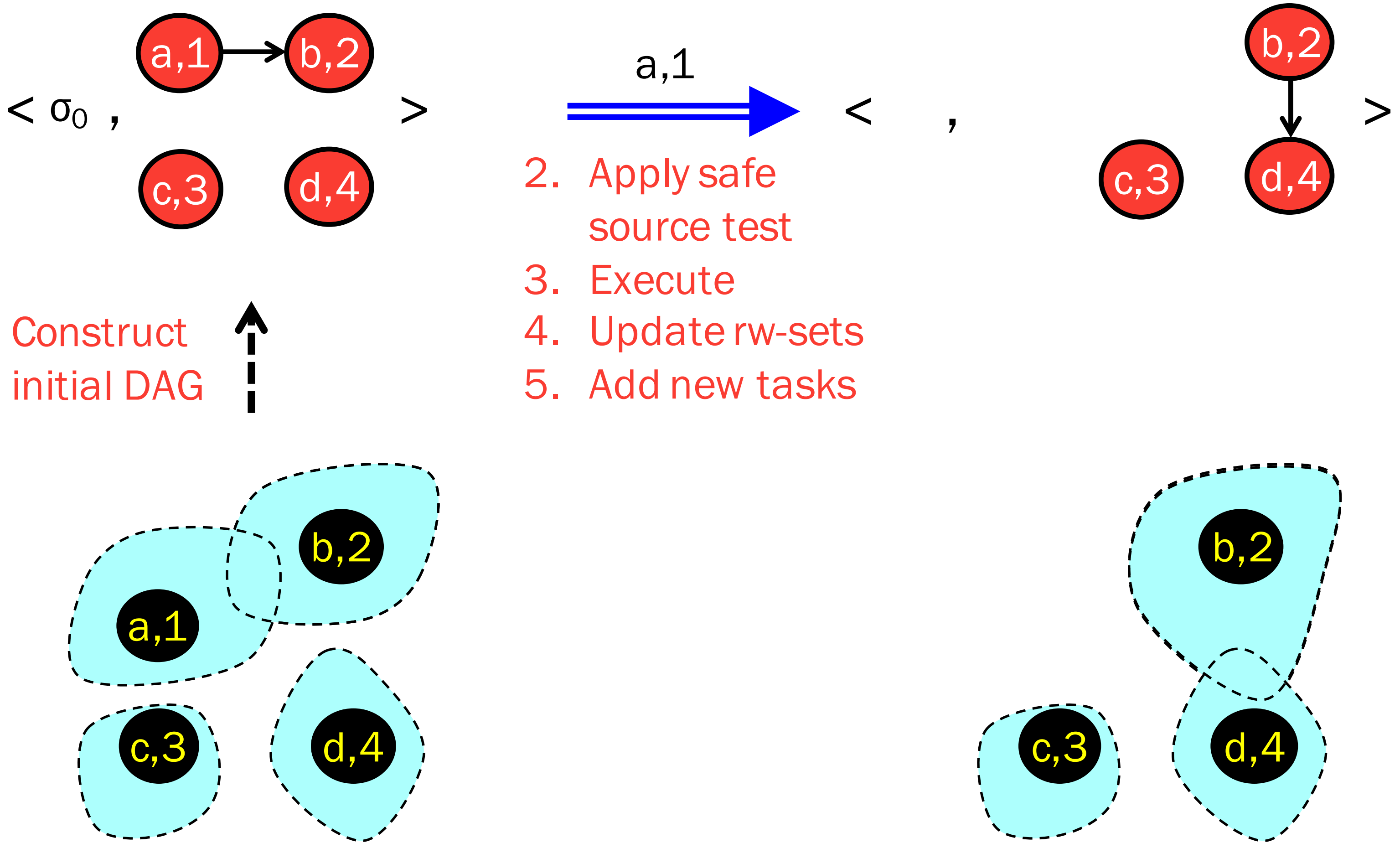

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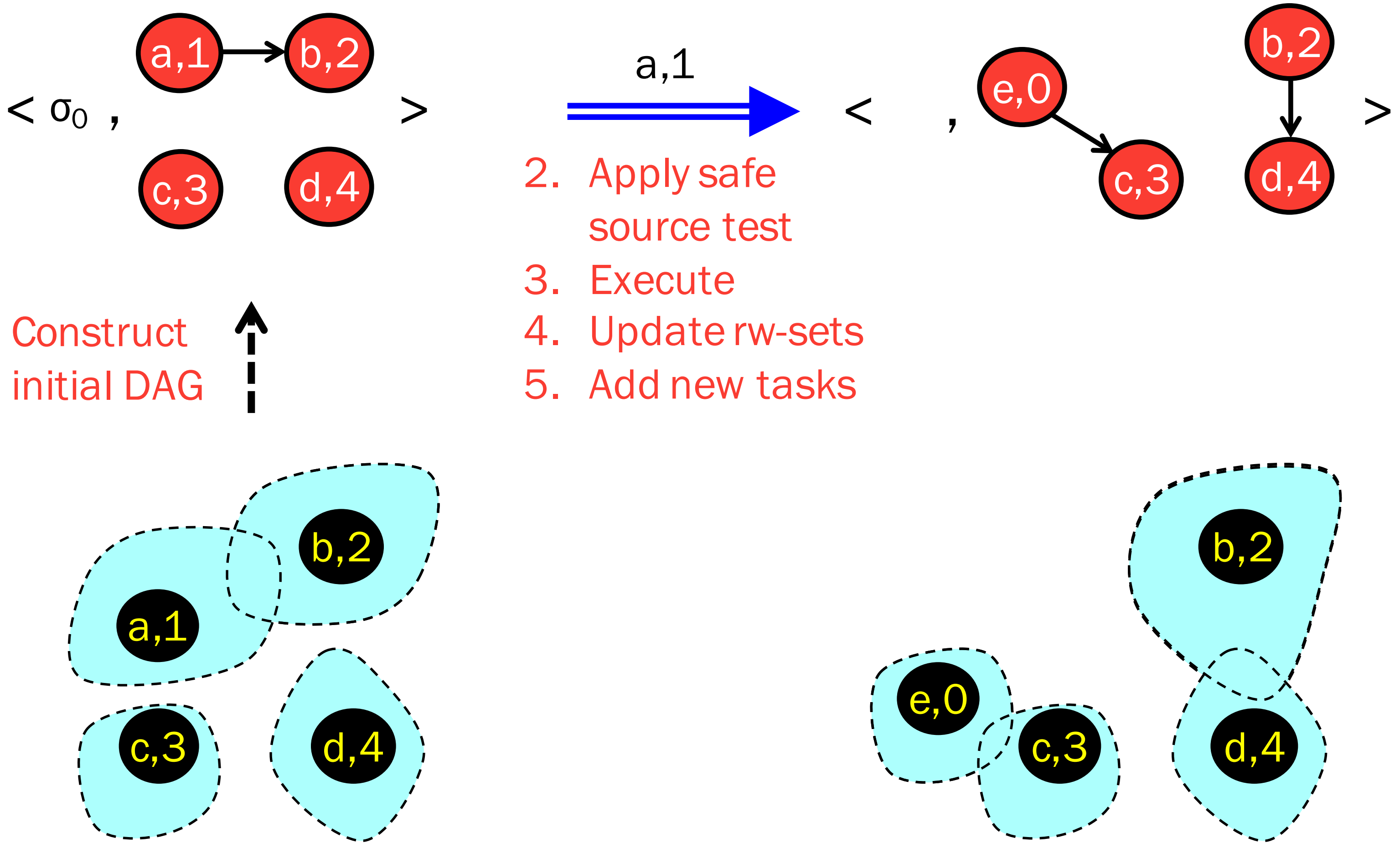

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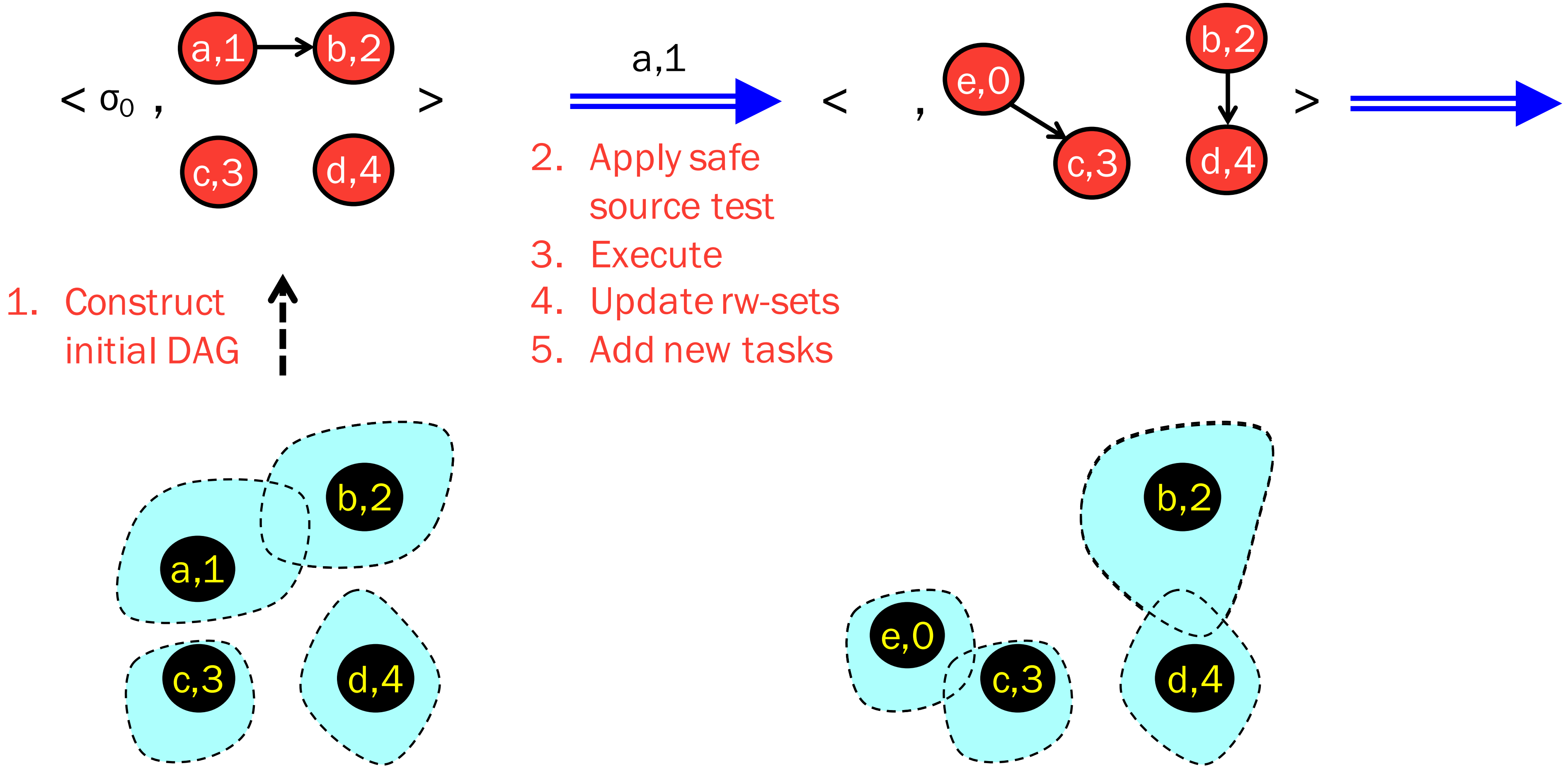

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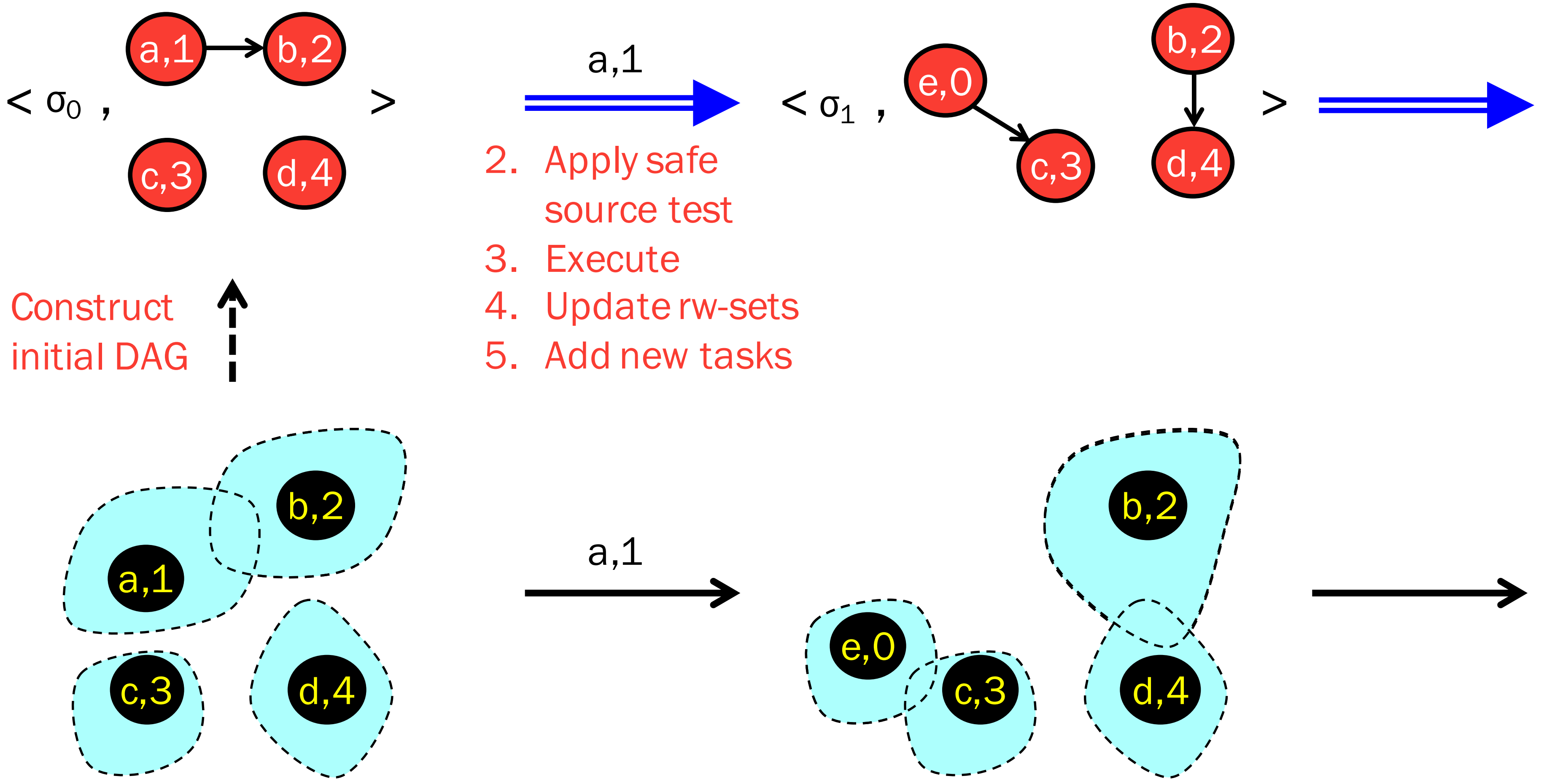

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KDG Specializations

Opportunities

- Each step needs a barrier
- Task's rw-set potentially updated several times prior to execution

KDG Runtime

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Program Properties

KDG Runtime

Application Programmer

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KDG Runtime

Program Properties

- Sources
  - In general: safe source test could inspect entire state
  - Local safe source test
  - Stable source (sources are safe)
- RW-sets
  - In general: task could change other tasks' RW-sets
  - Non-increasing RW-set
  - Structure-based RW-set
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  - In general: task could create new tasks at any priority
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- Remove unnecessary barriers given program properties
- Construct KDG for prefix of tasks
- Use different DAG representations

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Application Programmer

KDGs in Action

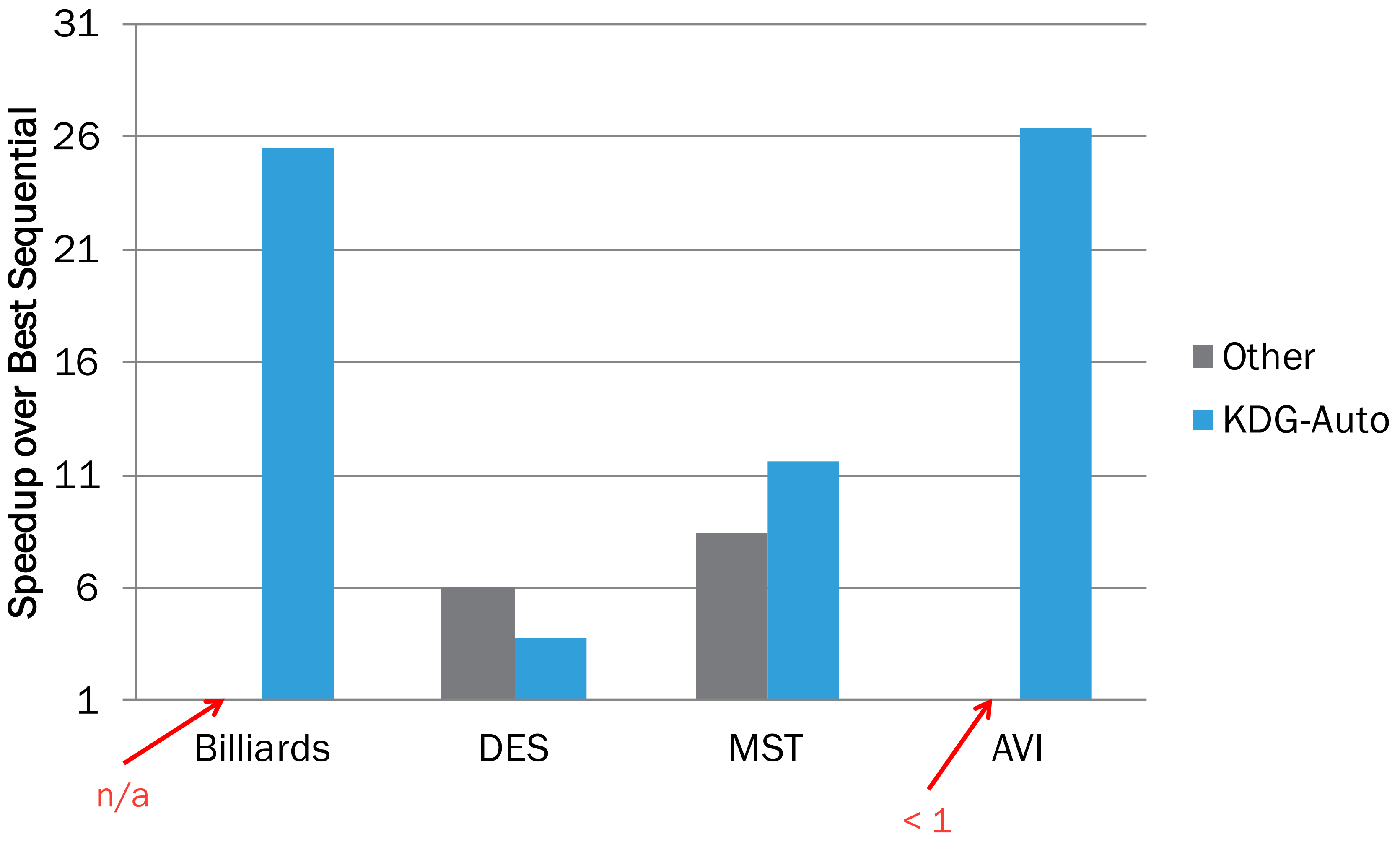
- Application programmer
  - Writes programs with ordered loops
    - Loop body must use provided data structure library
    - Loop properties provided via annotations
    - Loop body must read all elements before modifying any (cautious)
- KDG runtime (in Galois system)
  - Uses library API to track rw-sets at runtime
  - Selects executor based on annotations

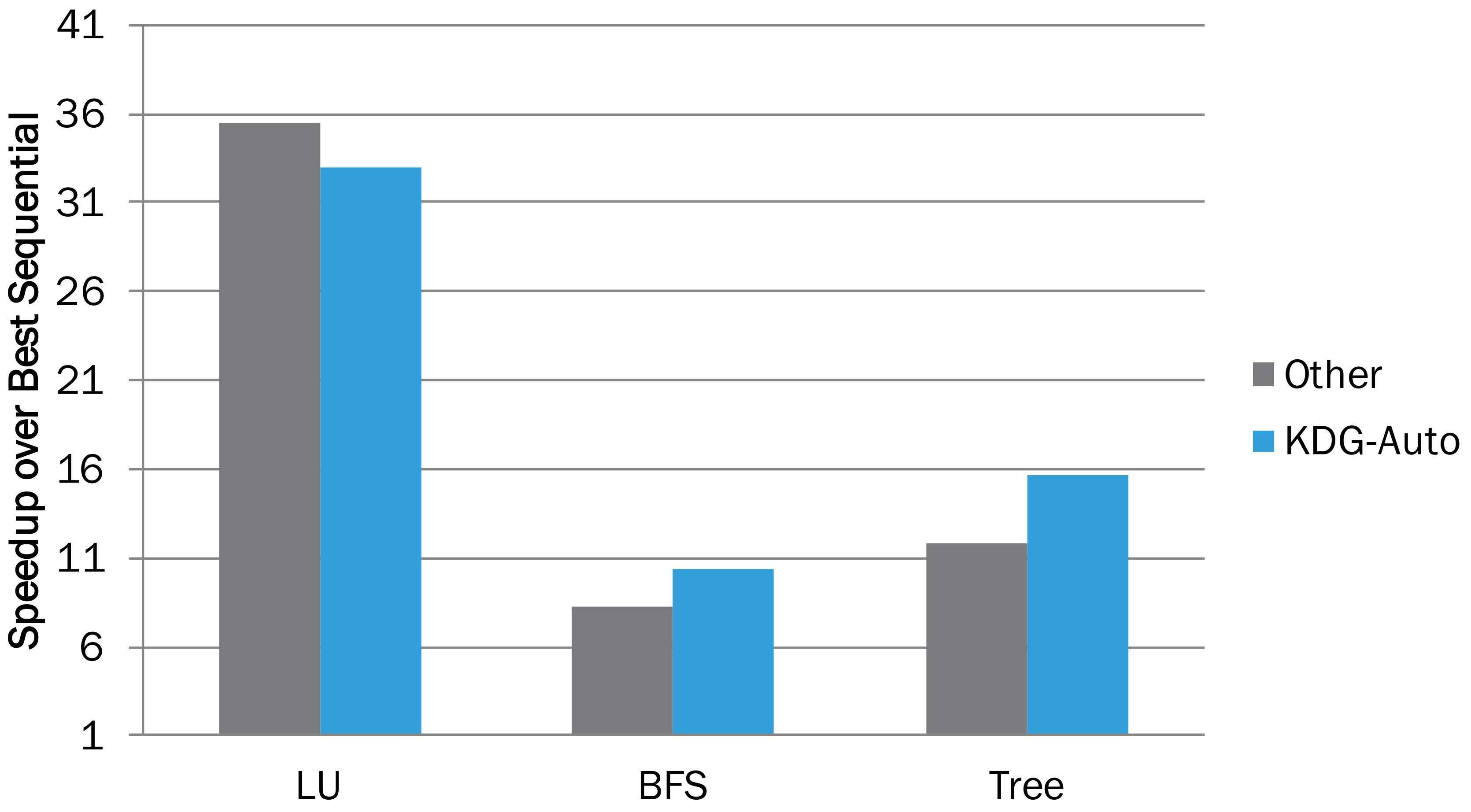
```
Graph g = ...
Set<Event> E = ...

@hasStructuredRWSets
@monotonic
foreach Event e in E orderedby e.t
  process(e, g)
  if *
    E.push(newE)
```

Evaluation

- 7 applications
  - From billiards simulation (hard-to-parallelize) to tree traversal (well supported by prior work)
- 2 types of programs
  - Other
    - 3rd-party handwritten, application-specific, OpenMP tasks, Cilk
  - KDG-Auto
    - Ordered loops + program property annotations
- 40-core, shared-memory machine


Speedup over Best Sequential
31
26
21
16
11
6
1
Billiards
DES
MST
AVI
n/a
< 1
■ Other
■ KDG-Auto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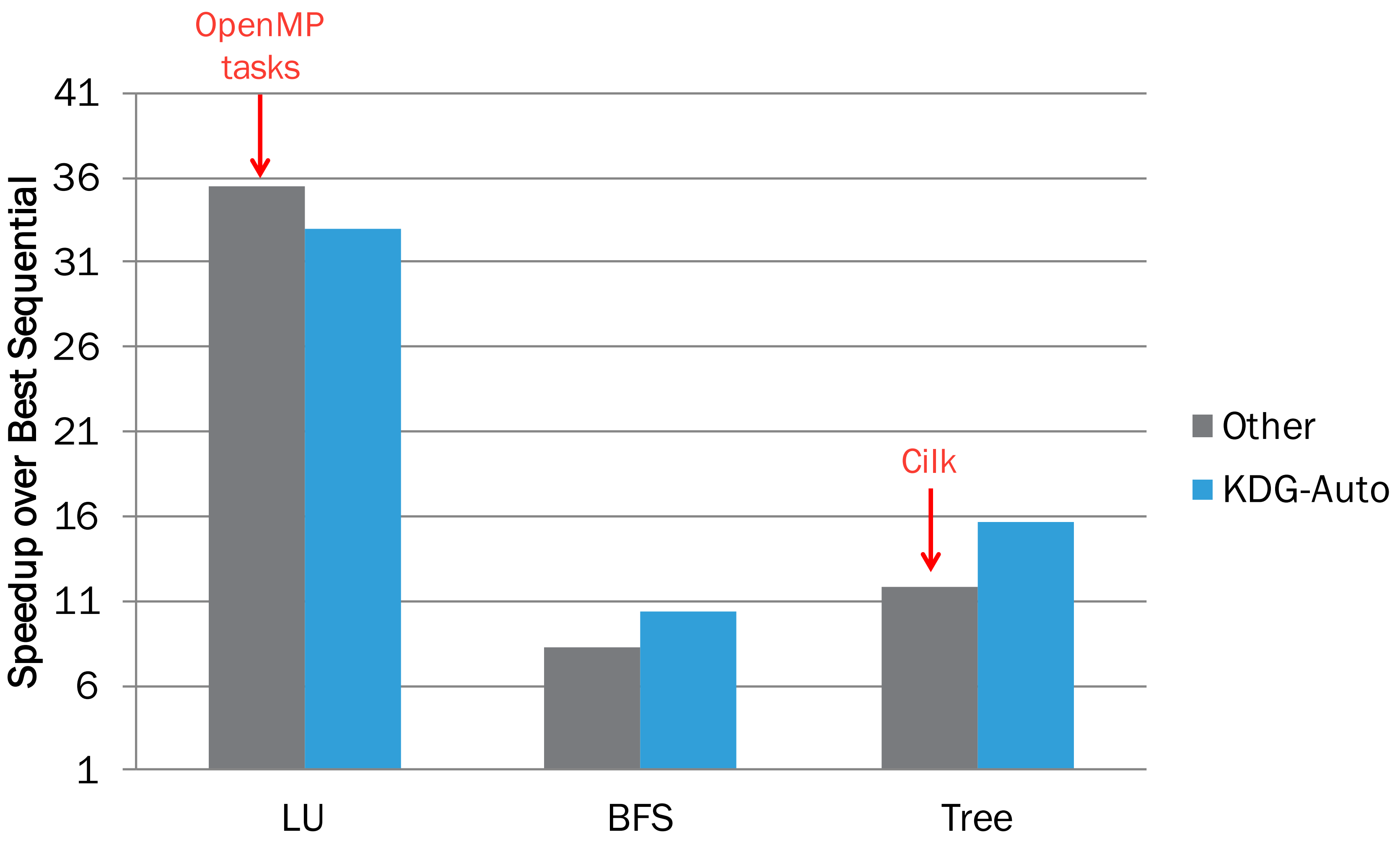
36
31
26
21
16
11
6
1
LU
BFS
Tree
Other
KDG-Auto



OpenMP tasks
Cilk
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Summary

- Problem
  - Dependence graph scheduling is insufficient for many ordered programs
- Solution
  - Develop general KDG executor
  - Specialize executor according to small number of program properties

"It is a mistake to try to look too far ahead. The chain of destiny can only be grasped one link at a time."

-Winston Churchill

Kinetic Dependence Graphs

M. Amber Hassaan,

Donald Nguyen,

Keshav Pingali

The University of Texas at Austin