# Partition Configuration for Real-Time Systems With Dependencies

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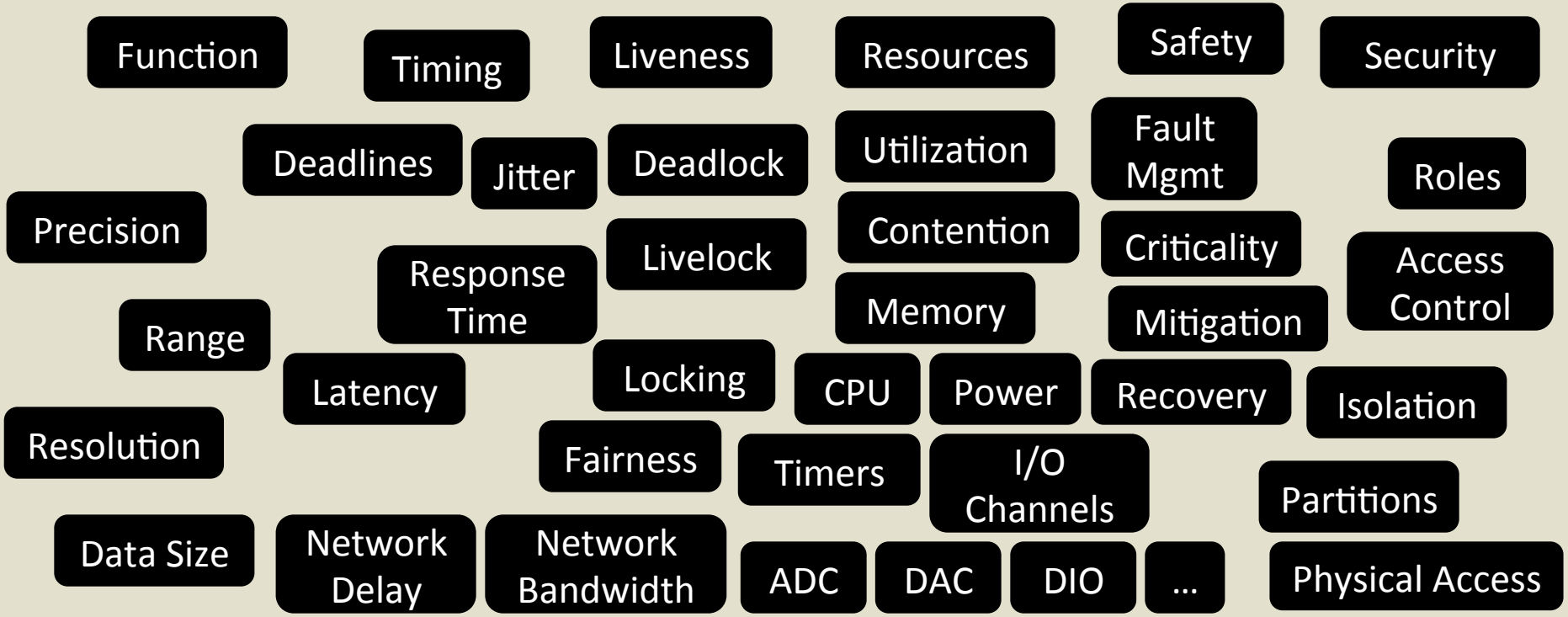
# Big Picture: One Difficulty With Design

Real-time system design is difficult because of the coupled nature of analysis problems.

Expressive tools and flexible system configuration options make design easier, but can make analysis more difficult.



# Big Picture: Flexibility is Important

- We want to keep design flexibility, but reduce complexity.
- For RT system designs, favor specification by constraints
- Feed back the effects of design choices to the modeler
  - What can be inferred from what we know about the system (e.g. requirements)?
  - Make it easy to see or predict the effects of design choices or configuration changes
- Determine configuration bounds within constraints

# Partitioned Real-Time Systems

Partitioning is provided by the RTOS to isolate the resource usage of groups of tasks:

- Used to isolate application vendors from each other (large critical systems)
- Used to isolate security layers
- Generally, partitions are used to isolate applications from access, faults, and failures in other applications running on the same hardware.

FOR OUR PURPOSES WE ACCEPT ALL REASONS FOR ISOLATION!

**Our theoretical examination:**

What happens to end-to-end latency when different partition configurations are chosen for a given task set with a strong set of dependencies?

Partitioning may impact application latency in significant ways.

# Approach: Graphs

**What's specified or assumed?**

- Tasks with dependencies (polar directed acyclic graph)
- Graph executes cyclically
- Buffered synchronous data transfers between tasks
- Task durations are known

- Constraints:
  - Affinity – schedule these in the same group
  - Conflict – never schedule these together

- Scheduling algorithm for partitions – we're using simple static schedulers, which are common for partitions.
- No preemption in partitions or tasks

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**FRAMEWORK RATIONALE**

- Graphs are easy to visualize
- Graphs and constraints are representationally compatible with our RT software design tools
- Framework handles all of the relationships in our problem

- Simple scheduling and non-preemption because you have to do all of the execution end-to-end (intend to relax this…)

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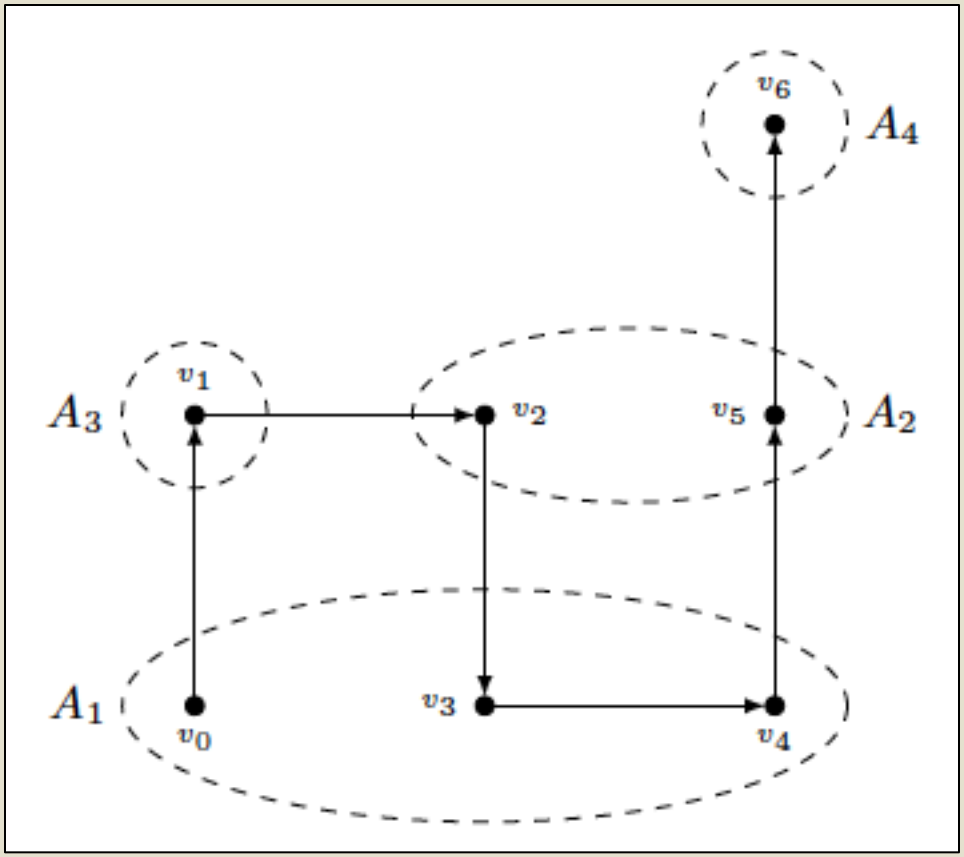
**Which quantities are dependent?**

- Number of partitions
- Which tasks live in each partition? (subject to constraints)
- Partition durations and periods
- Application latency (source to sink)

**What's tricky?**

- Configuration choices affect the critical path
- Task graph ordering search problems are intractible (in general)
- therefore, the layout of tasks within partitions is also intractable

# Specifications: Task Graph and Partitioning Constraints




**Task dependency graph (TDG)**
*G = (V, E)*

Task set $V = \{ v_0, \ldots, v_6 \}$
Affinity sets $A = \{ A_1, \ldots, A_4 \}$
No conflicts for now…

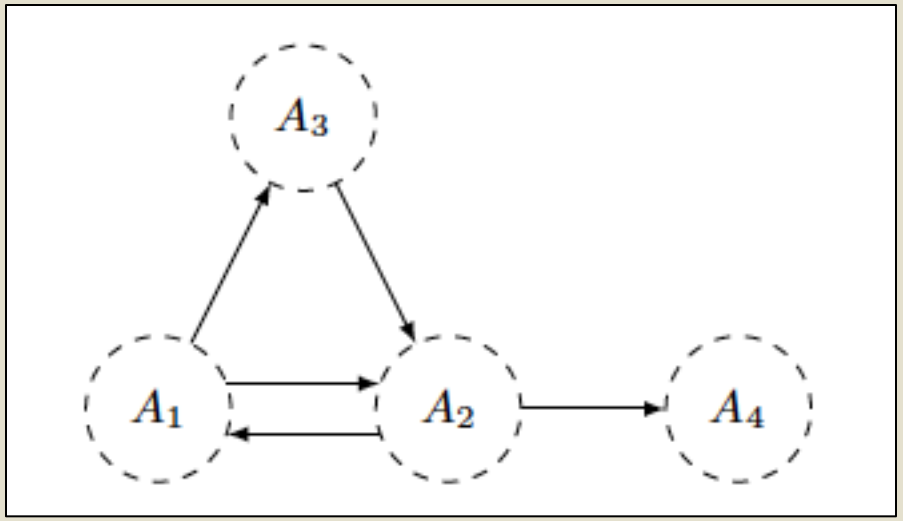
**Basic Properties**

- Consistency – two tasks can have affinity, or conflict, (or nothing) but not both
- Partition membership – in the end, each task will belong to exactly one partition
- Transitivity – a task in conflict with one task in an affinity set is also in conflict with all other members of the affinity set

# Specification: Abstractions and Observations

**Affinity Dependency Graph (ADG)**

- Current affinity sets are vertices
- Abstracted dependencies between them:
  - at most one edge in each direction
  - edge exists if any task dependencies exist between affinity sets
  - NOT ACYCLIC!




Use ADG to make decisions about grouping tasks into partitions

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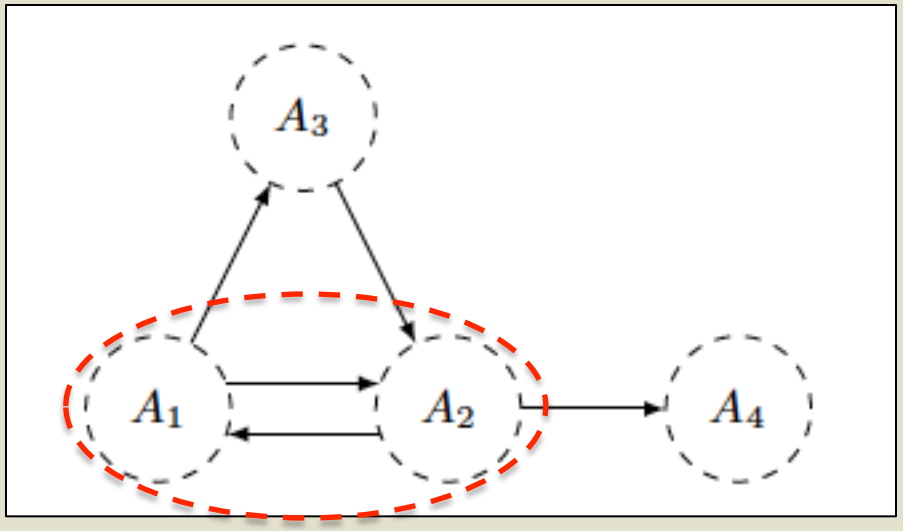


**Merge Operation**

- Combine two affinity sets into one
  - Remove intervening edges
  - Maintain external edges
- Use this to simplify ADGs – why?

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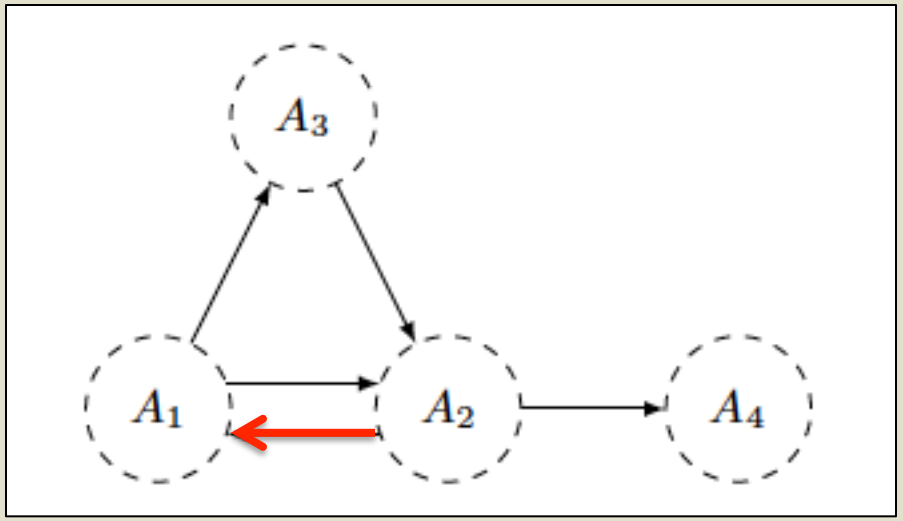
Partition configuration changes can have fine-grained effects on end-to-end latency.

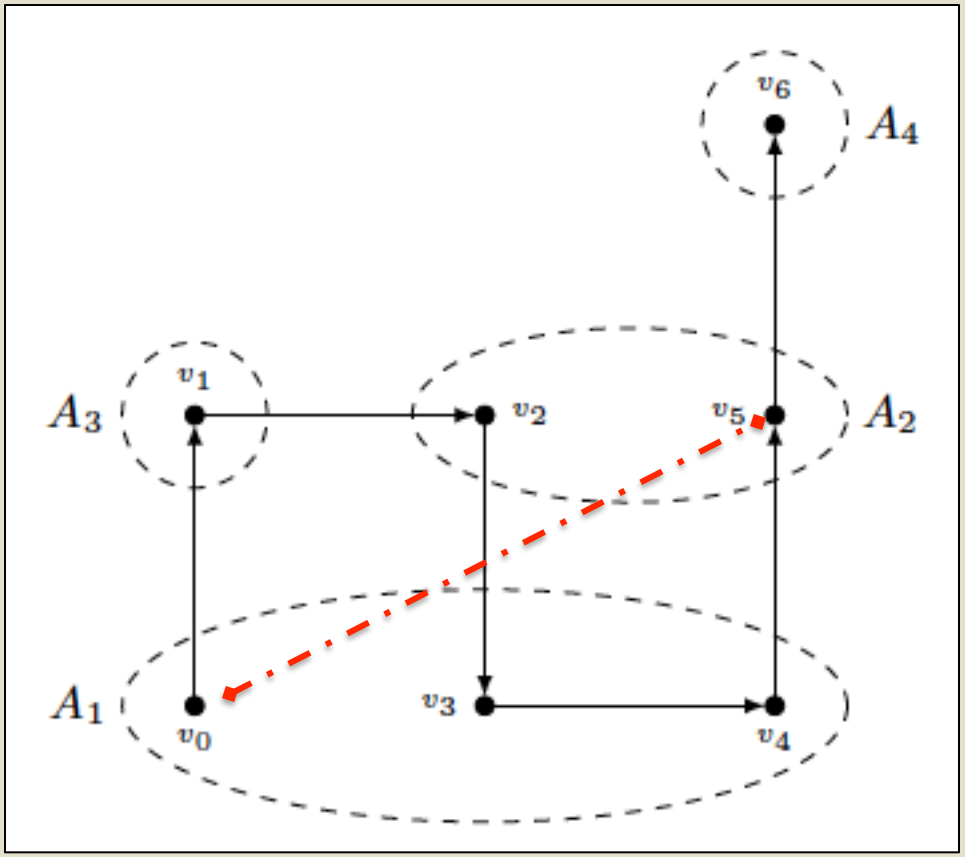
We deliberately avoided those and considered abstractions that expose large-impact effects.




**Back Edge**

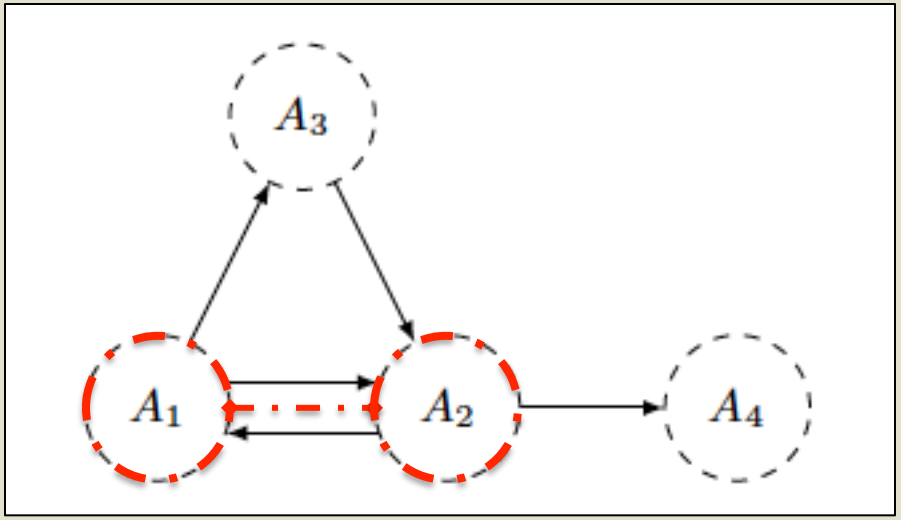
- In the ADG, a back edge completes one or more cycles (in the sense of DFS)
- To schedule a back edge, we must revisit these vertices again in the cycle:
  - For harmonic partitions, this means two or more instances per cycle
  - For round-robin partitions, this means multiple cycles

# Specification: Conflicts and Partitions

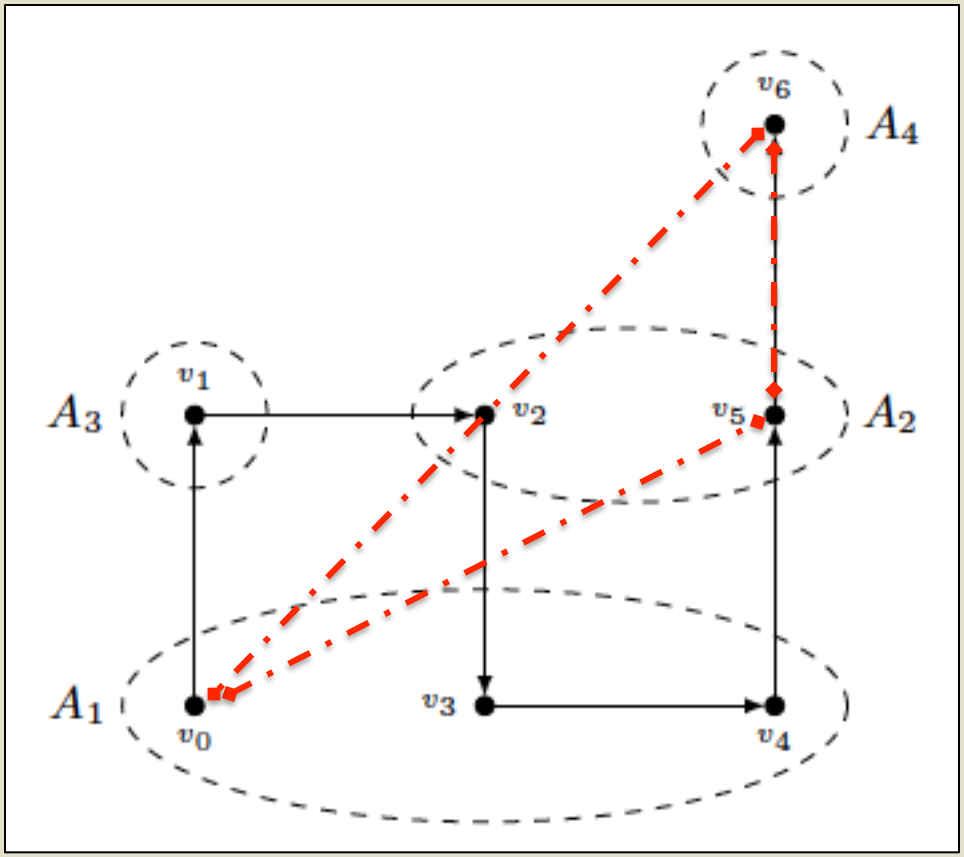



**Conflict Graphs**

Another graph over either the TDG or the ADG illustrates the defined conflicts, as shown



# Theoretical Insights: Conflicts and Partitions

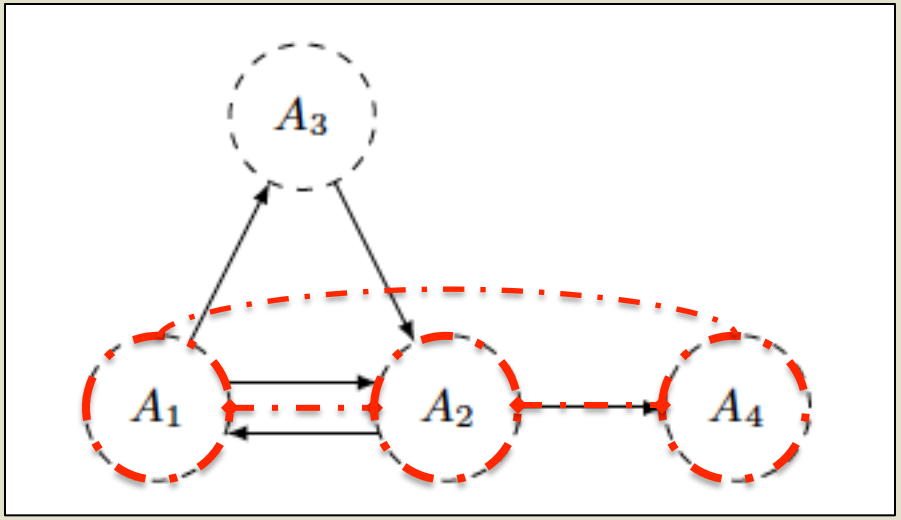



The upper bound on the number of partitions is the number of affinity sets + the number of unassigned vertices.

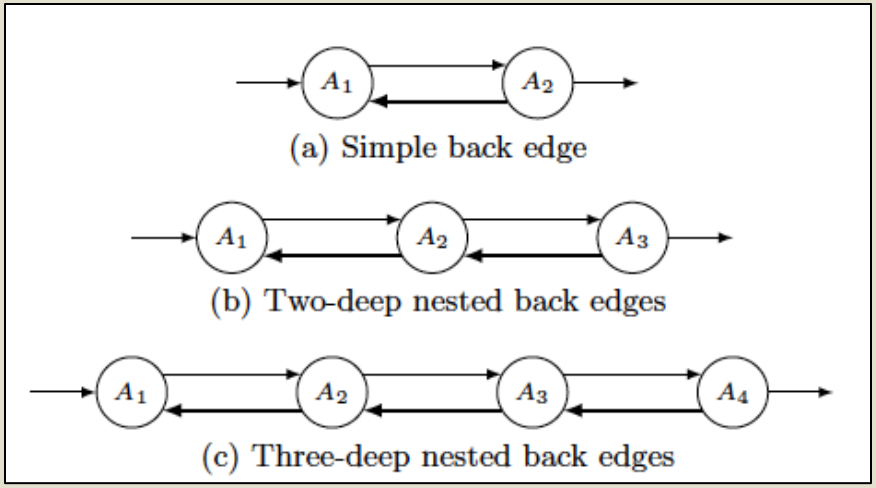
**Conflict Graphs**

The number of partitions has to be greater than or equal to the largest conflict clique.

This is chosen over both graphs, but the largest ADG conflict clique is never smaller than the TDG conflict clique, so it's sufficient to consider the ADG conflict graph.



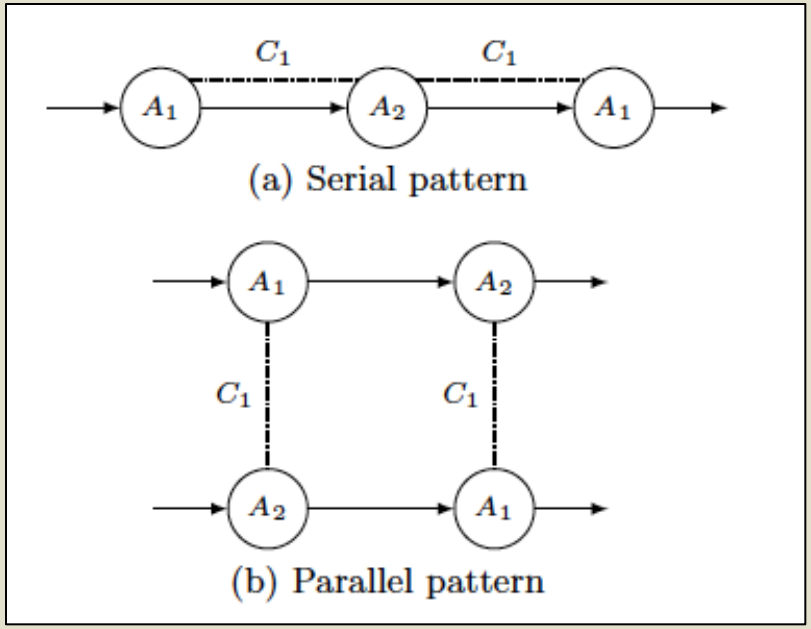
# Theoretical Insights: Back Edges




A few structures always lead to the formation of back edges in a merge – in the figure below, affinity sets with the same labels will be merged.

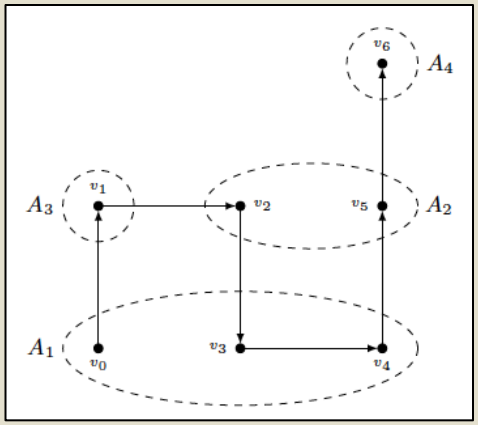
Multiple back edges in an ADG do not necessarily lead to multiple schedule repetitions:

- repetitions may be scheduled concurrently
- unless they are nested (shown above)
- at least one extra repetition will occur per level of nesting



# Execution With a Flexible Partition Scheduler

- In this case, the partition execution "follows" the task execution, repeating any partition as many times as necessary in the cycle.
- Just perform some useful ordering of the tasks, and play them in the right order.
- This gives the tightest result.

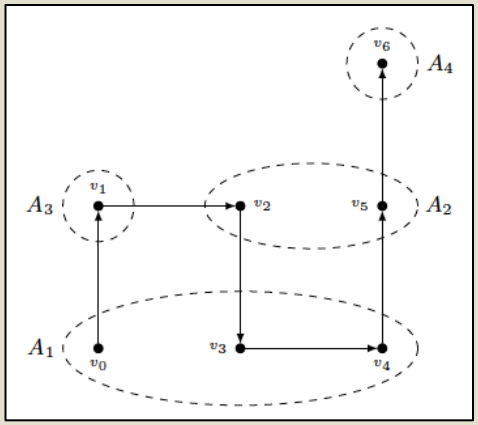



| Task | Start Time | Duration | Partition Instance | Offset | Partition Duration |
|---|---|---|---|---|---|
| $v_0$ | 0 | 70 | $A_{11}$ | 0 | 70 |
| $v_1$ | 70 | 63 | $A_3$ | 70 | 63 |
| $v_2$ | 133 | 33 | $A_{21}$ | 133 | 33 |
| $v_3$ | 166 | 30 | $A_{12}$ | 166 | 71 |
| $v_4$ | 196 | 41 | | | |
| $v_5$ | 237 | 39 | $A_{22}$ | 237 | 39 |
| $v_6$ | 278 | 15 | $A_4$ | 278 | 15 |

At ISIS we now have a partitioned scheduler for Linux that can be configured to do it this way, so this isn't too far-fetched. It wasn't available in time for this paper.

# Execution With a Harmonic Partition Scheduler

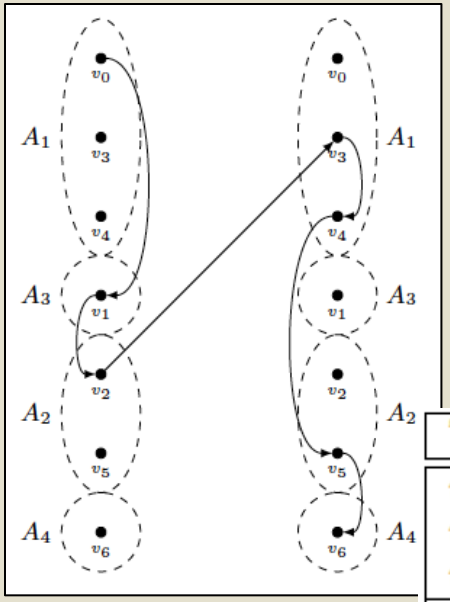
- This is a standard case for partition schedulers, and we solve it with a MILP.
- The tricky part is allowing tasks to belong to any instance – this is also encoded in the MILP (see constraint 7 in the paper).
- Since each partition instance has to have the same duration, the scheduling should be less tight.
- The MILP objective tries to squash the extra space as much as possible.




| Task | Start Time | Duration | Partition |
|---|---|---|---|
| $v_0$ | 0 | 70 | $A_{11}$ |
| $v_1$ | 100 | 63 | $A_3$ |
| $v_2$ | 163 | 33 | $A_{21}$ |
| $v_3$ | 248 | 30 | $A_{12}$ |
| $v_4$ | 278 | 41 | |
| $v_5$ | 411 | 39 | $A_{22}$ |
| $v_6$ | 481 | 15 | $A_4$ |

# Execution With a Round-Robin Partition Scheduler

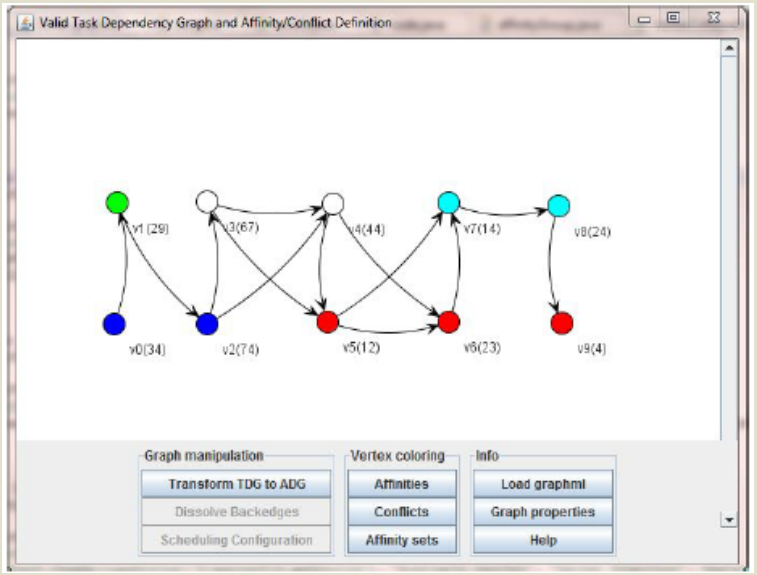
- Round robin partition scheduling is easy to implement, and therefore also common.
- The schedule takes a full cycle penalty due to the back edge in the ADG.
- Merging affinity sets $A_1$ and $A_2$ (in the absence of conflict constraints) would remove the penalty.
- The conflict relations and the affinity relations bound the extremes of partition number, so we can determine degrees of freedom in the configuration problem.
- This gives the longest latency result.



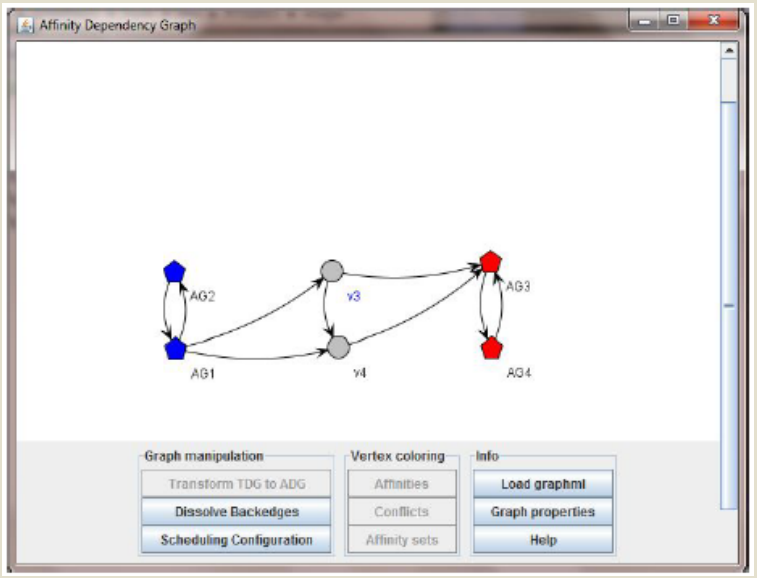

| Partition Scheduler | Latency |
|---|---|
| Flexible | 293 |
| Harmonic | 496 |
| Round-robin | 582 |

| Task | Start Time | Duration | Partition |
|---|---|---|---|
| $v_0$ | 0 | 70 | |
| $v_3$ | 70 | 30 | $A_1$ |
| $v_4$ | 100 | 41 | |
| $v_1$ | 141 | 63 | $A_3$ |
| $v_2$ | 204 | 33 | $A_2$ |
| $v_5$ | 237 | 39 | |
| $v_6$ | 276 | 15 | $A_4$ |
| $v_0$ | 291 | 70 | |
| $v_3$ | 361 | 30 | $A_1$ |
| $v_4$ | 391 | 41 | |
| $v_1$ | 432 | 63 | $A_3$ |
| $v_2$ | 495 | 33 | $A_2$ |
| $v_5$ | 528 | 39 | |
| $v_6$ | 567 | 15 | $A_4$ |

# Simulation Environment




TDG Example




ADG Example

- Input TDG is specified in GraphML (with a few slight tweaks)
- Affinity and conflict are included in the graph as attributes on vertices and edges
- We use the Java JUNG toolkit for graph visualization
- We can generate random problem instances algorithmically

# Future Work (and Work In Progress)

**Work In Progress**

- Validation of predicted results with F6 OS Linux partition scheduler
- Automation of the round-robin analysis
- A real-world application example

**Future Work (or slower work in progress…)**

- Good heuristics for choosing schedule orders
- Automatic calculation of nesting depth
- Preemptive task schedulers
- Multiple local processors
- Distributed processors with network delays

# Questions?

Those interested in trying our tools can contact me:
Joe Porter (jporter@isis.vanderbilt.edu)