LUCAS: Latency-adaptive Unified Cluster Assignment and instruction Scheduling

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University of Edinburgh

LCTES 2013

Energy efficiency, VLIWs and Scheduling

- Mobile era.

Energy efficiency, VLIWs and Scheduling

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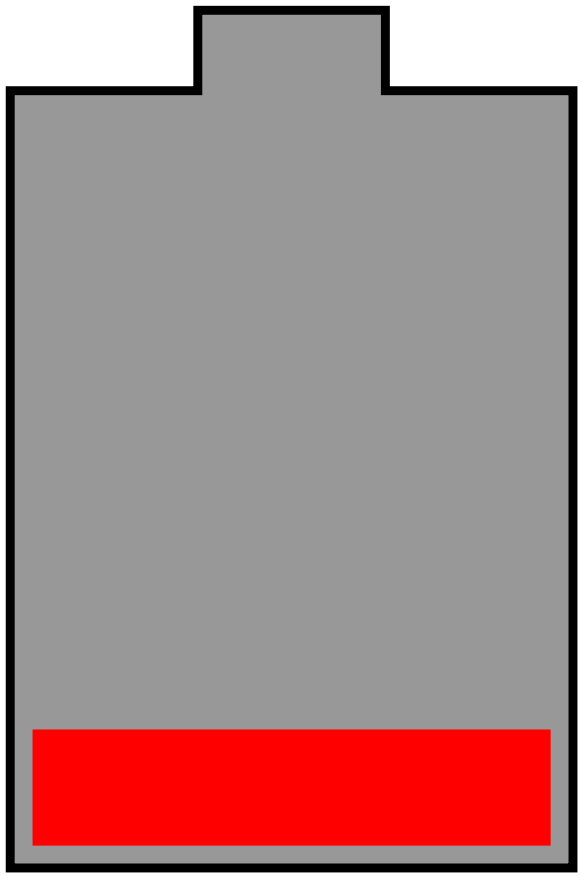
- Energy becomes a major design constraint.



Energy efficiency, VLIWs and Scheduling

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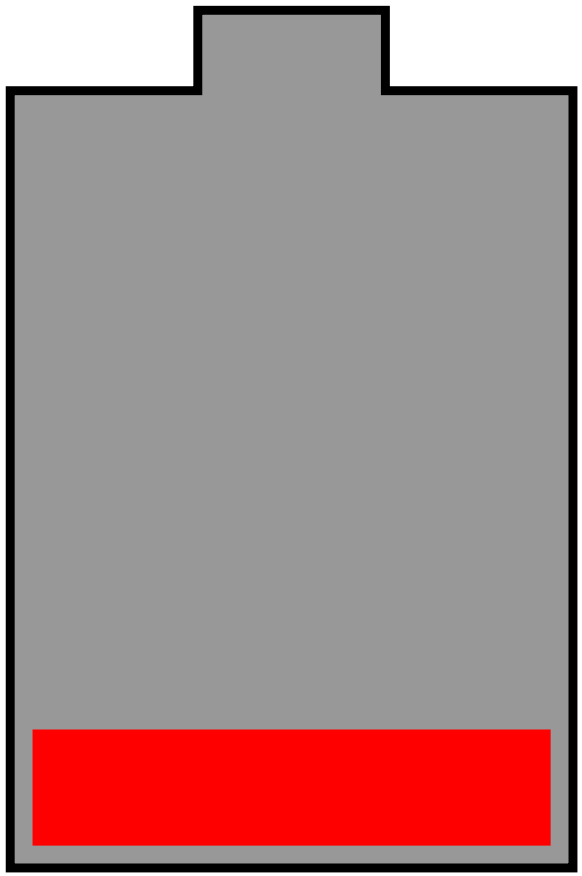

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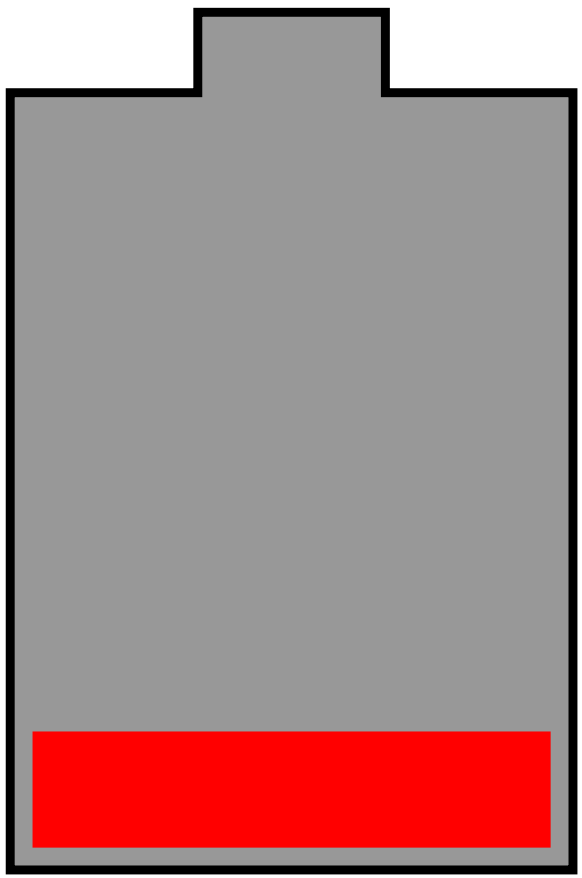
- VLIW processors: high-performance and statically scheduled.



Energy efficiency, VLIWs and Scheduling

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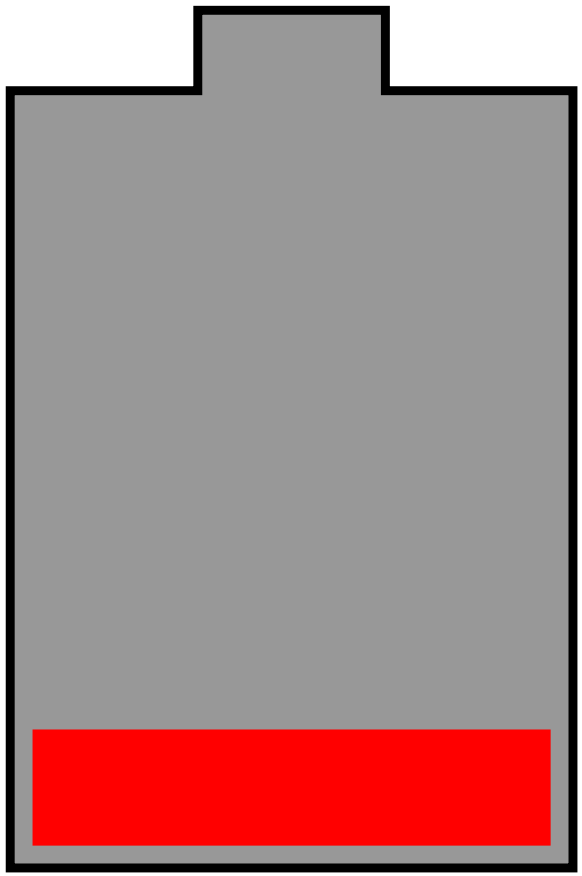
- VLIW processors: high-performance and statically scheduled.
- Clustered VLIW = scalable VLIW.



Clustered VLIW

- Scalable
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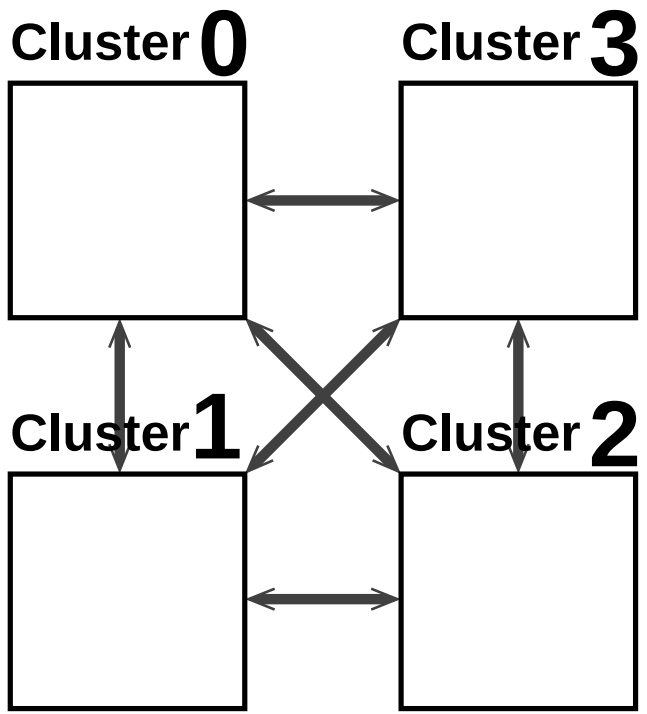

Clustered VLIW

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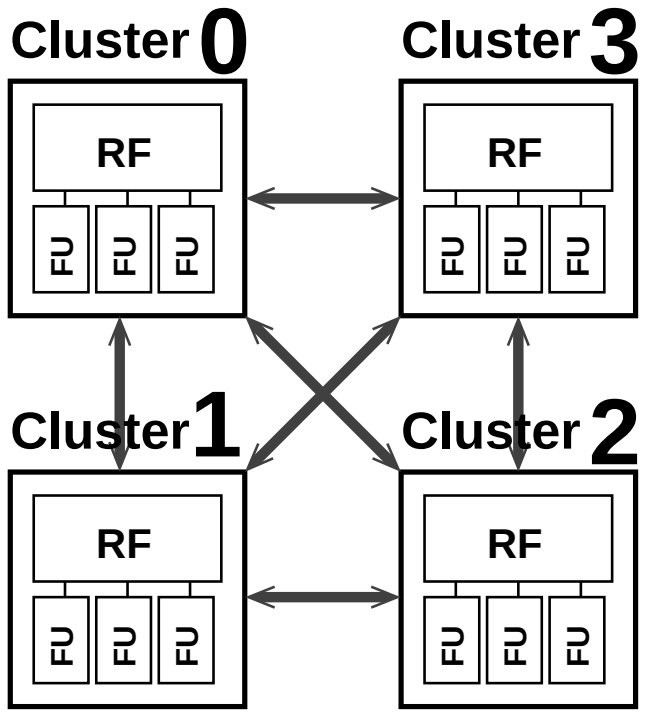
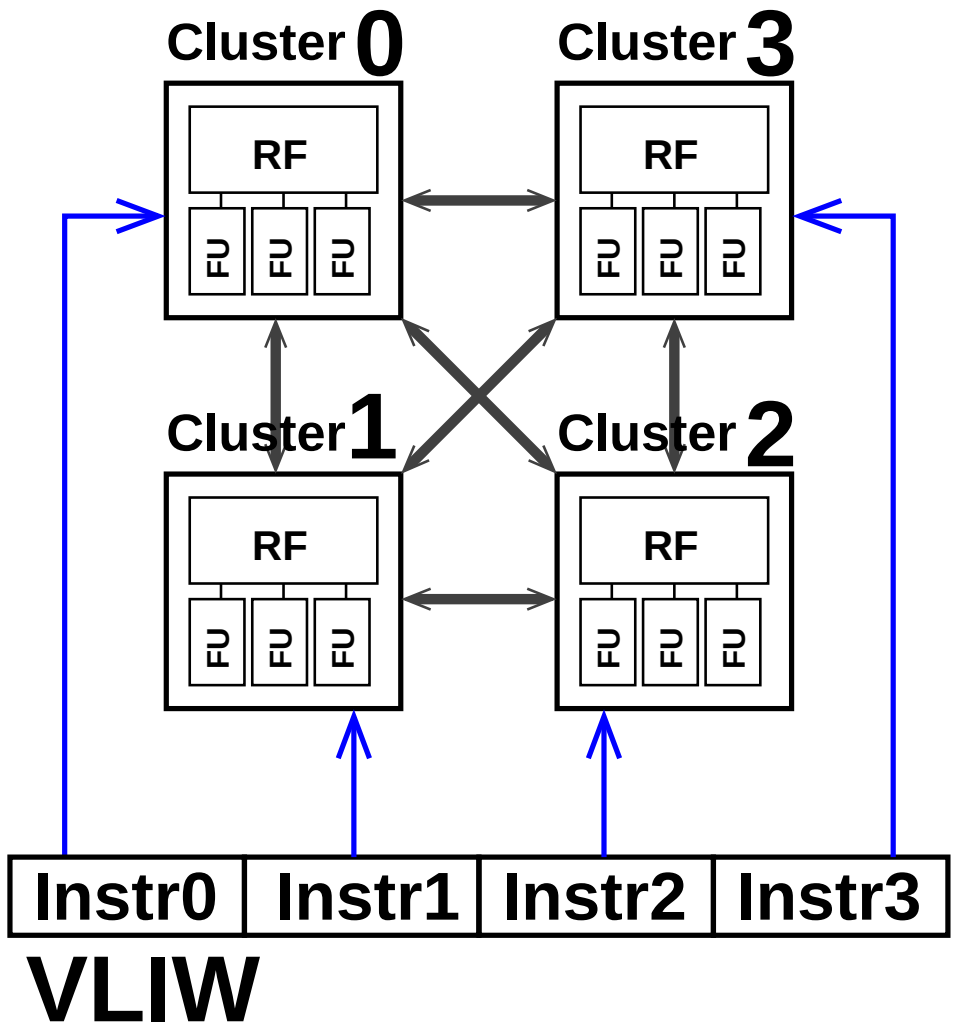


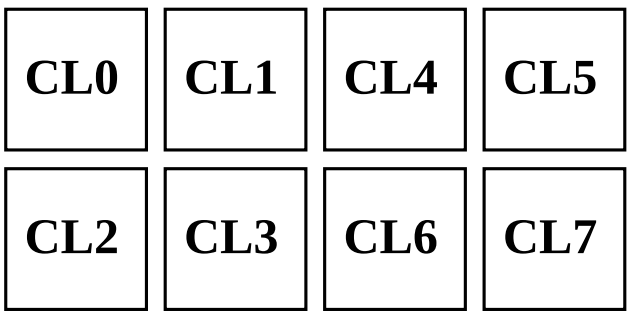
Clustered VLIW

- Scalable
- Energy efficient
- High frequency
- Inter-Cluster delay
- Relies on compiler
- Statically scheduled
- Explicit ILP



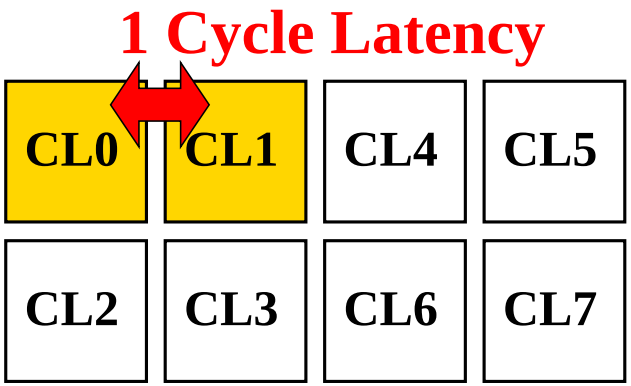
Problem: Many possible Inter-cluster latencies

- An application could map on any set of clusters.



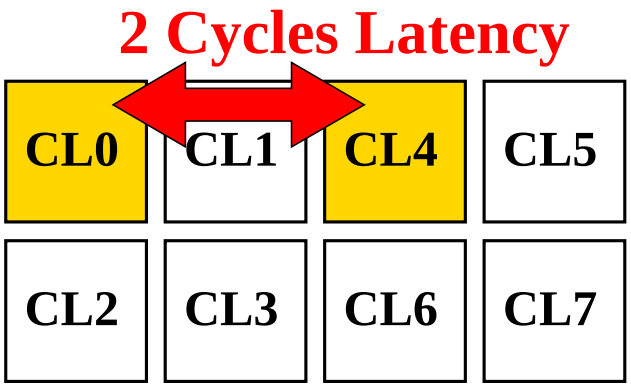
Problem: Many possible Inter-cluster latencies

- An application could map on any set of clusters.
- Low inter-cluster latency.



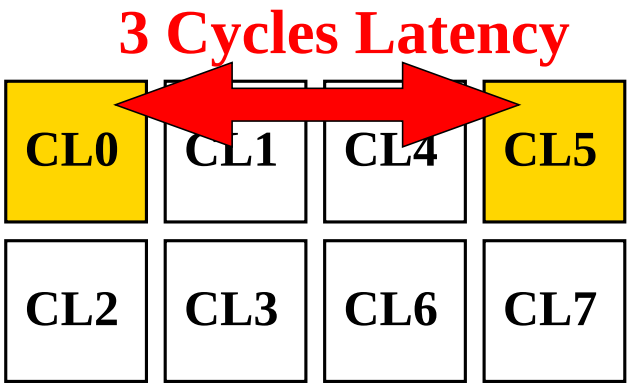
Problem: Many possible Inter-cluster latencies

- An application could map on any set of clusters.
- Low inter-cluster latency.
- Higher inter-cluster latency.



Problem: Many possible Inter-cluster latencies

- An application could map on any set of clusters.
- Low inter-cluster latency.
- Higher inter-cluster latency.
- Instruction Scheduler should adapt to all latencies.



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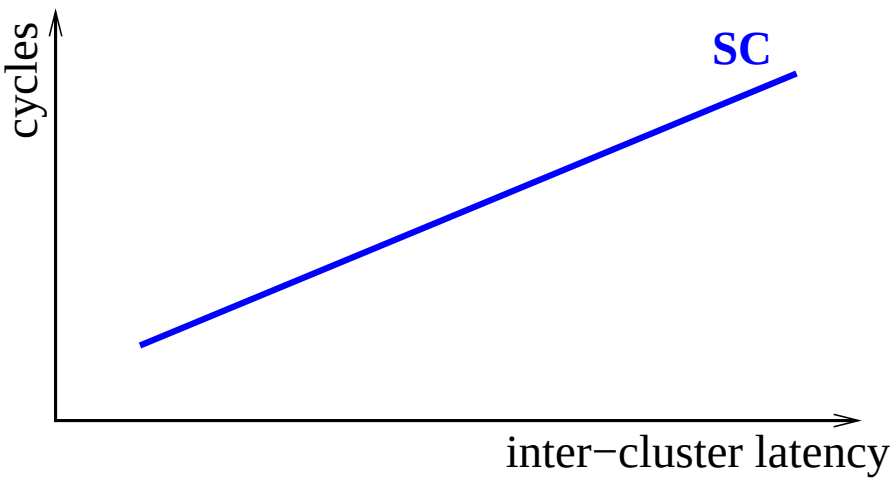

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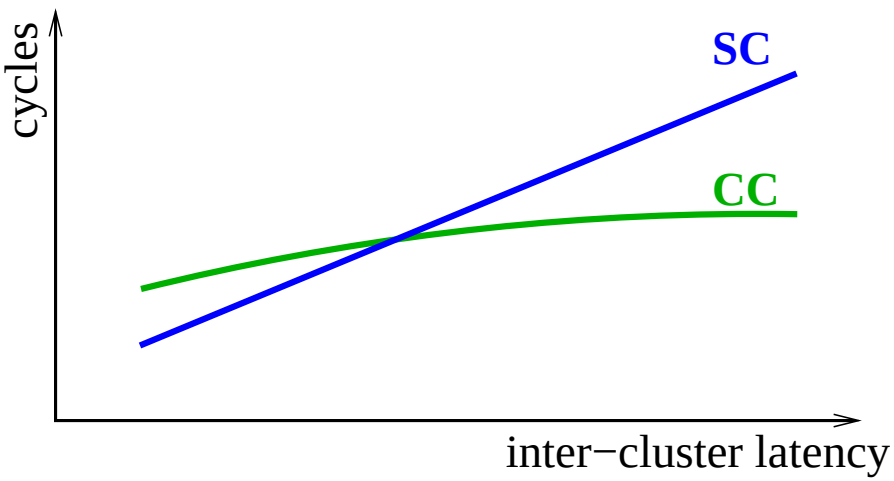

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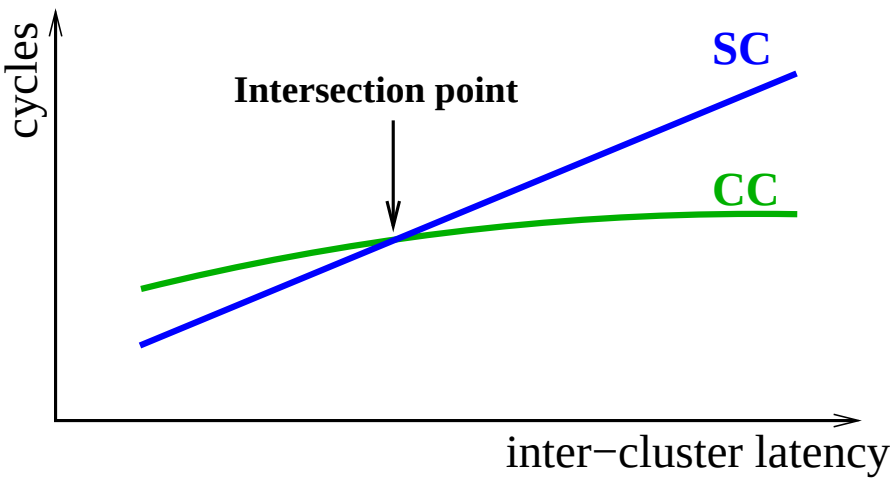

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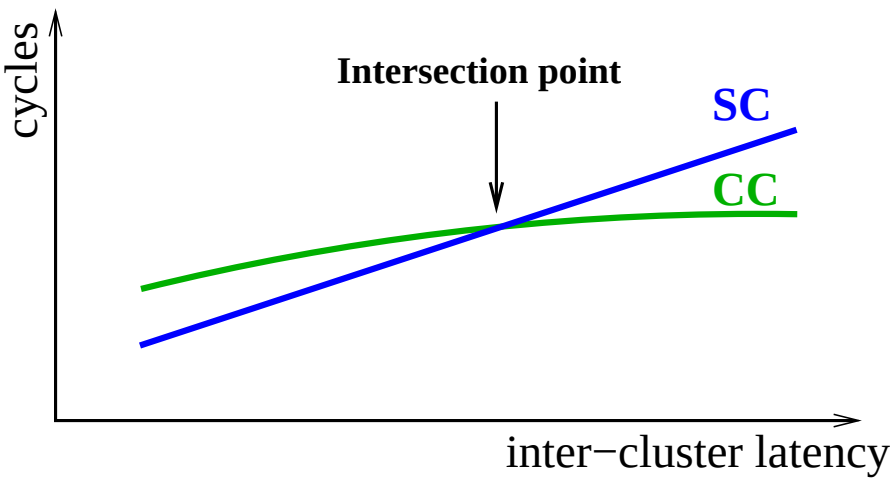

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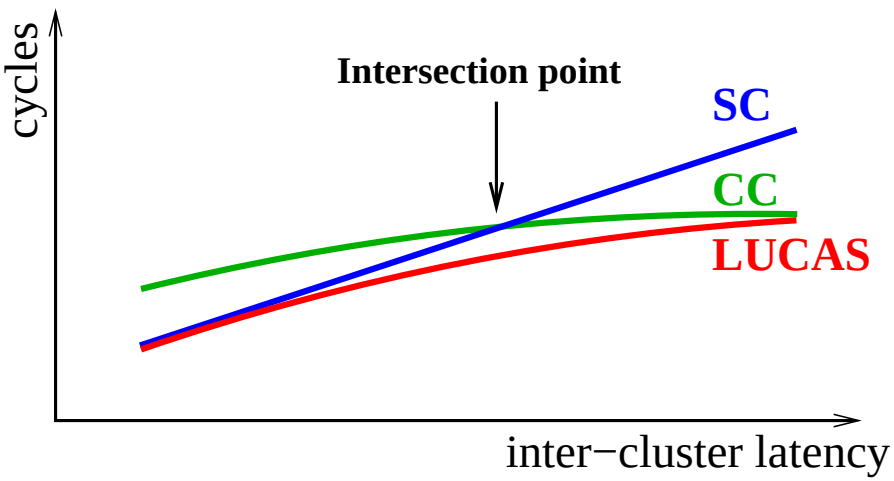
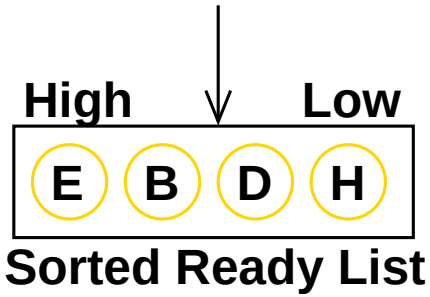
- When each performs best is benchmark dependent.
- Scheduler must generate good code under any inter-cluster latency.



Outline

LUCAS Scheduler



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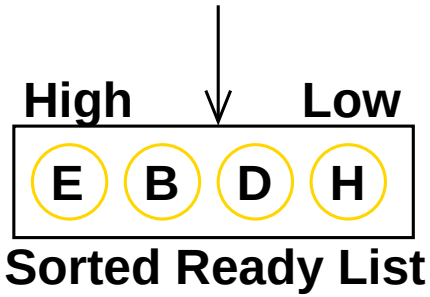

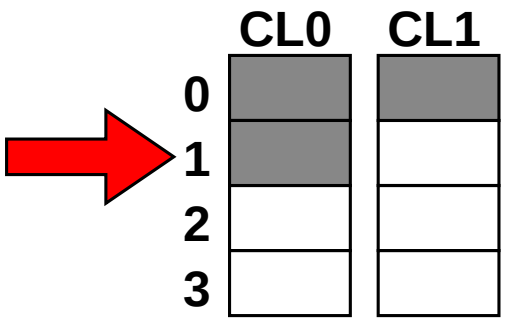

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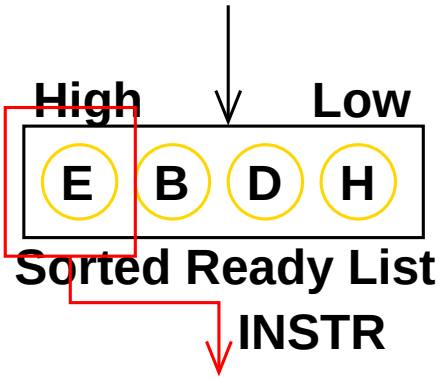

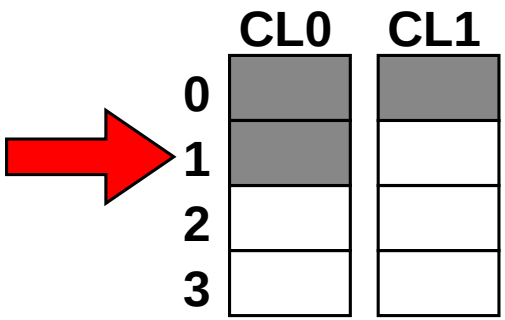

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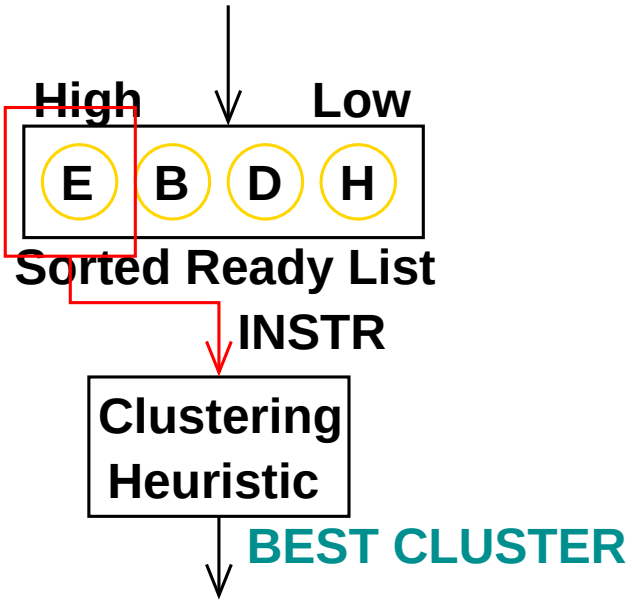

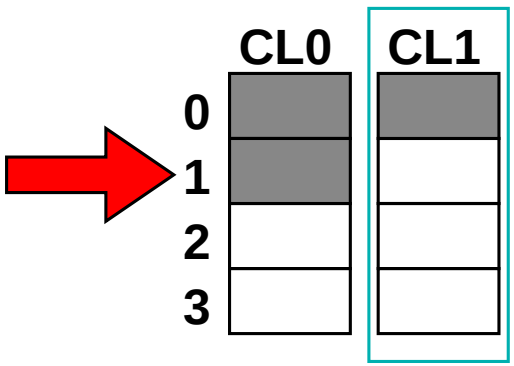

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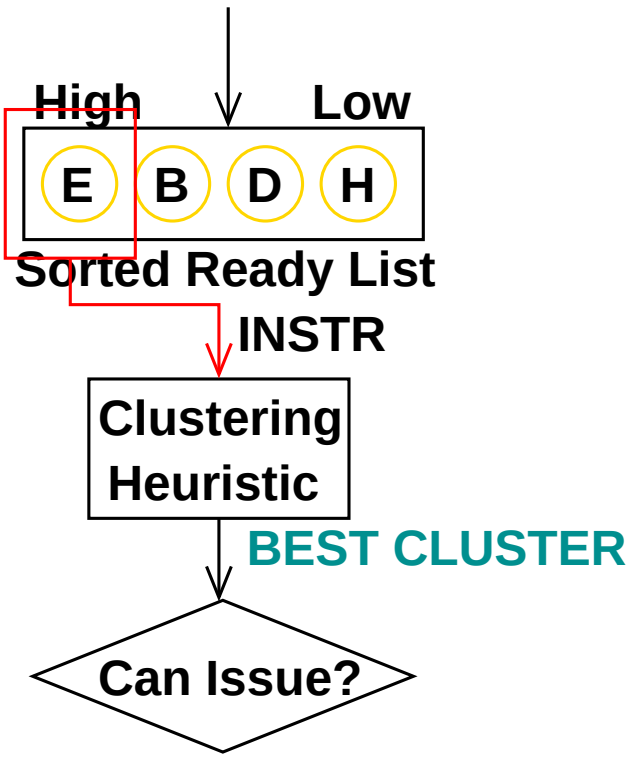

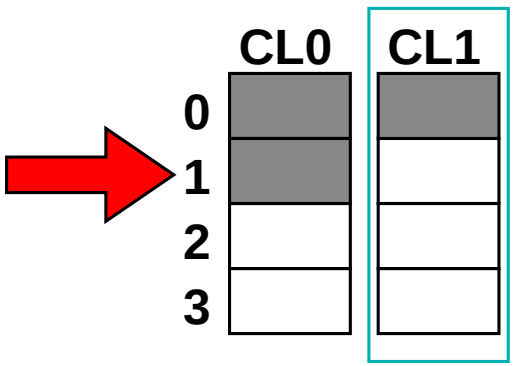

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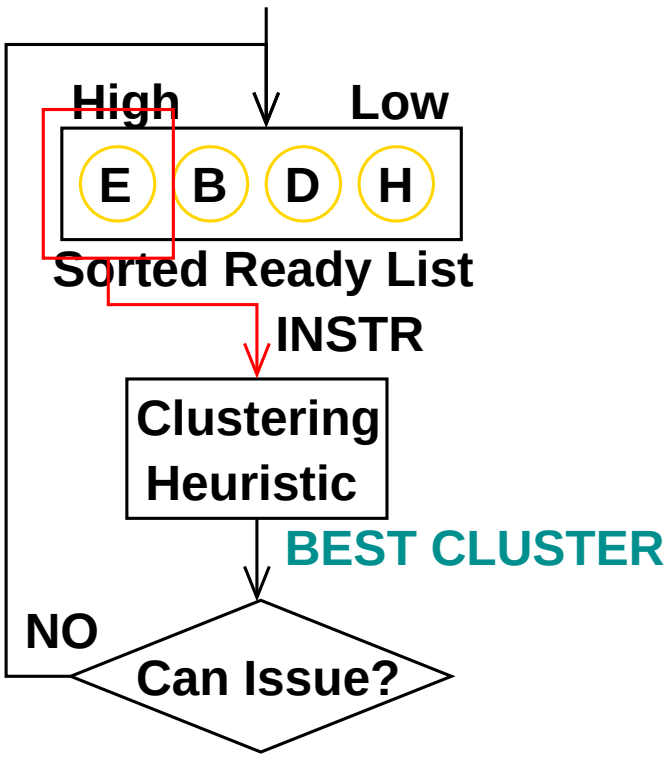

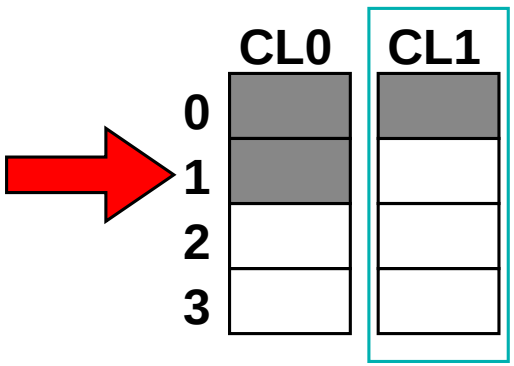

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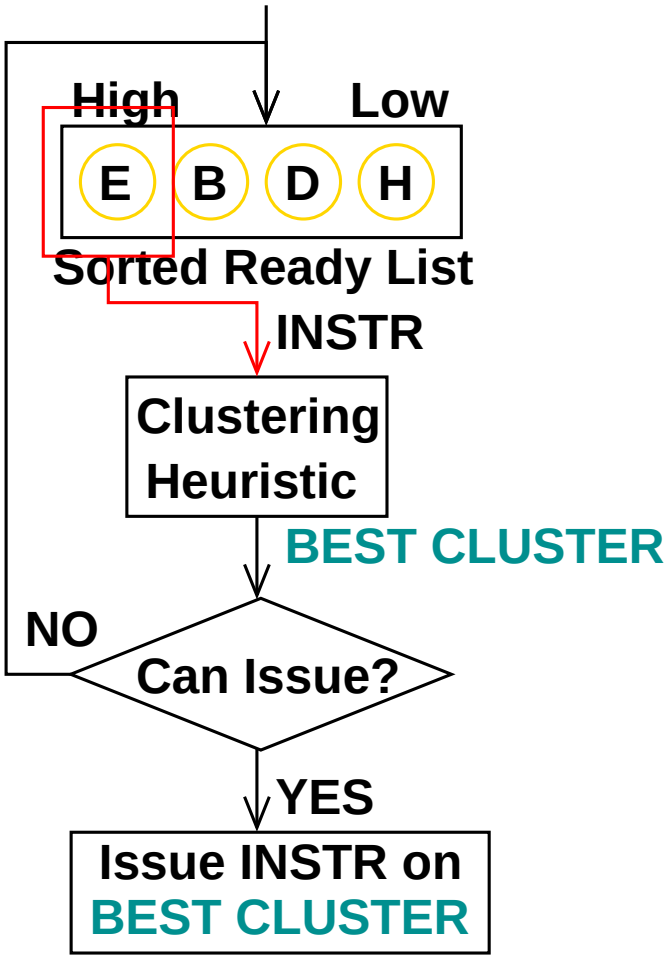

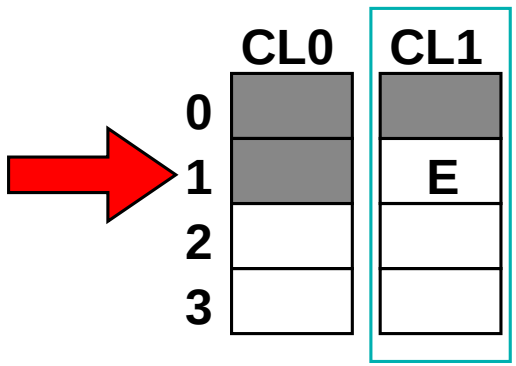

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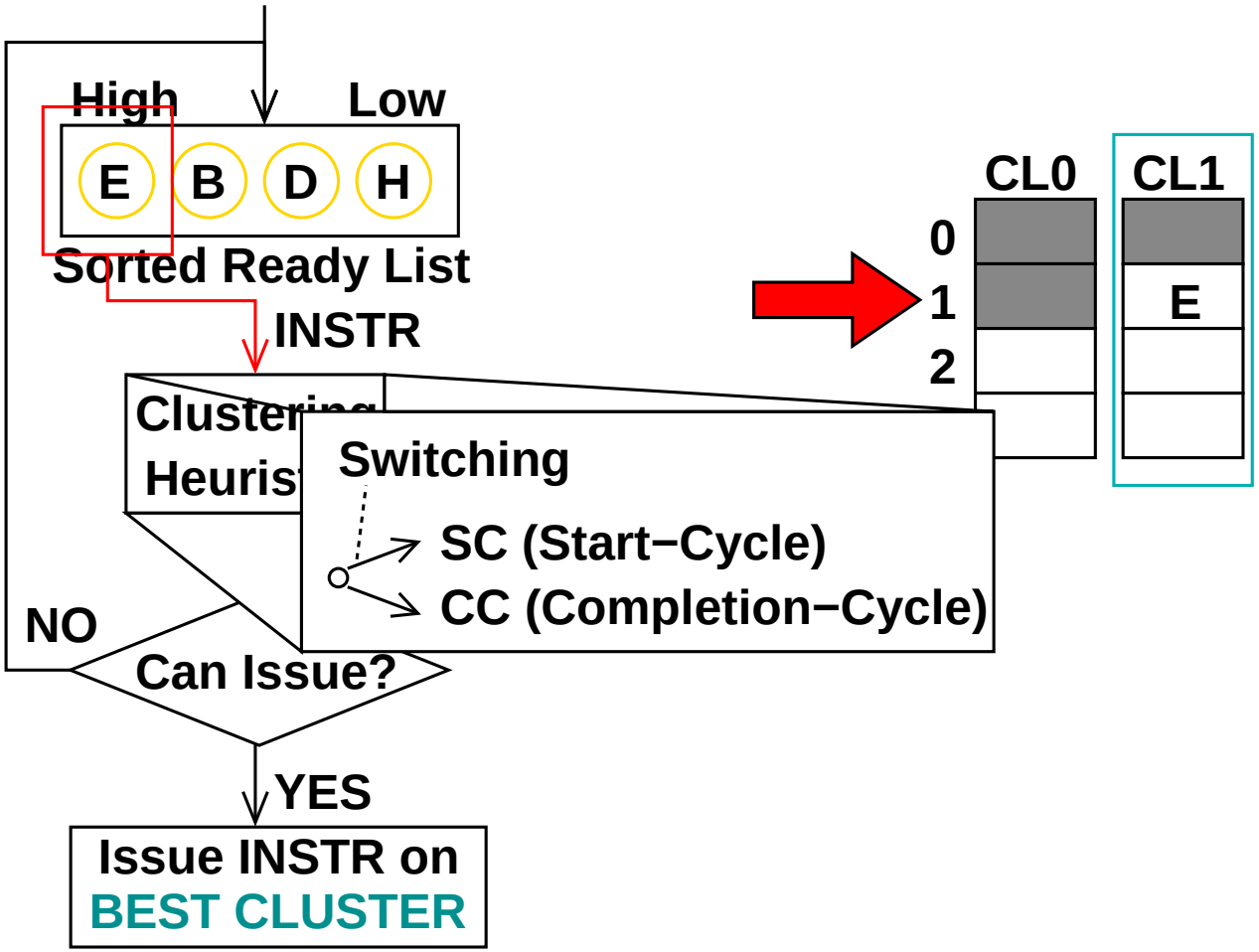
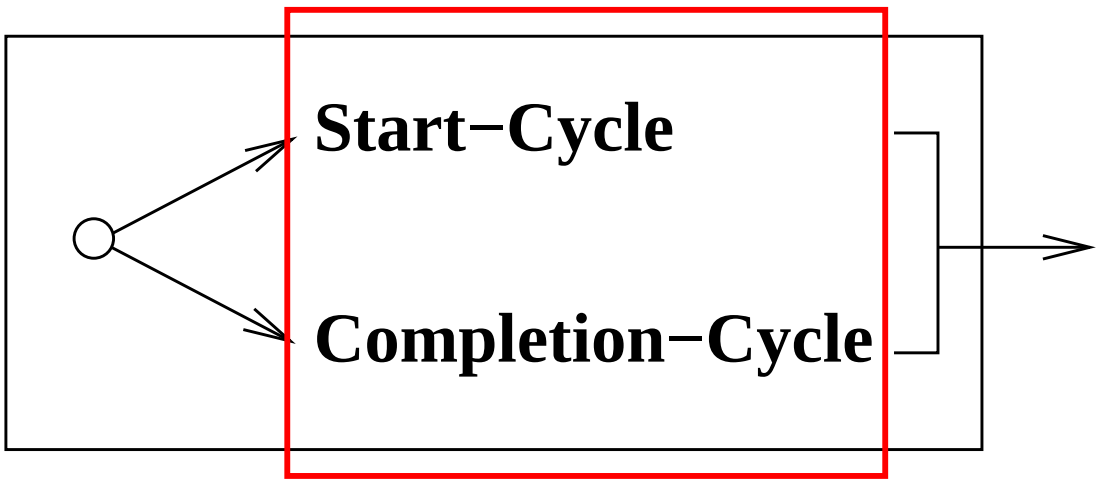


- Switch between aggressive SC and conservative CC at an instruction-level granularity

Clustering heuristics



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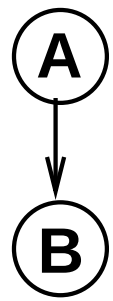
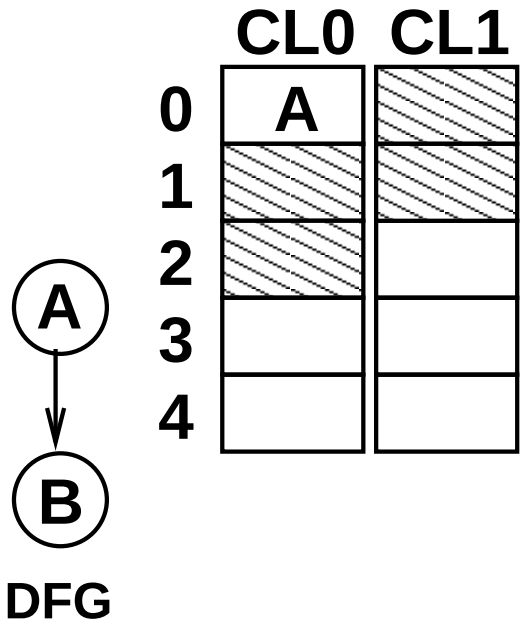


DFG

Clustering heuristics

- Start-Cycle (SC) is the earliest cycle an instr. can be scheduled at a given cluster. One-way inter-cluster latency.



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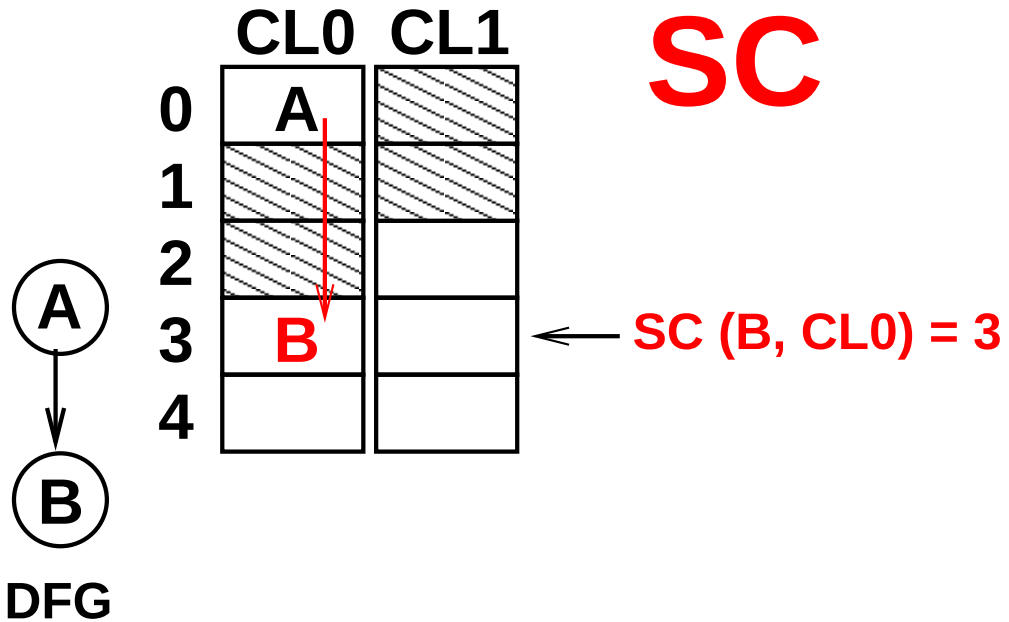

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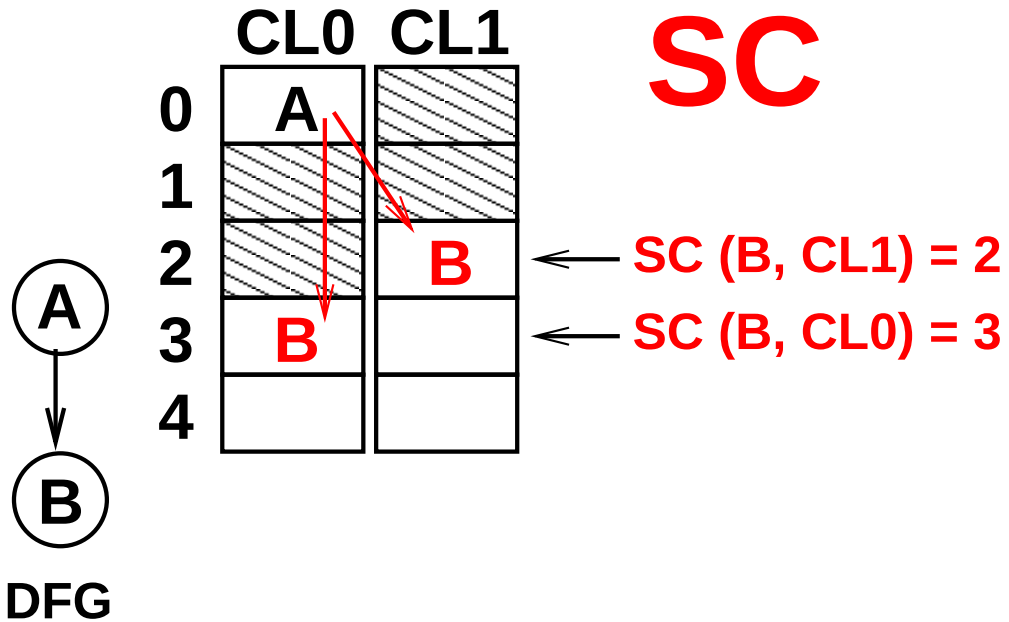

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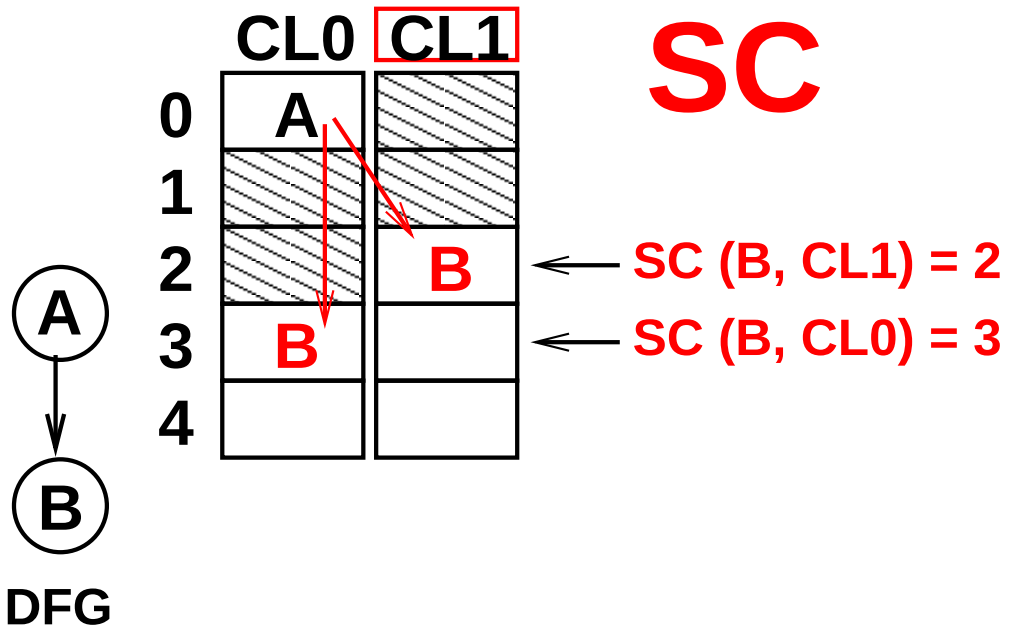

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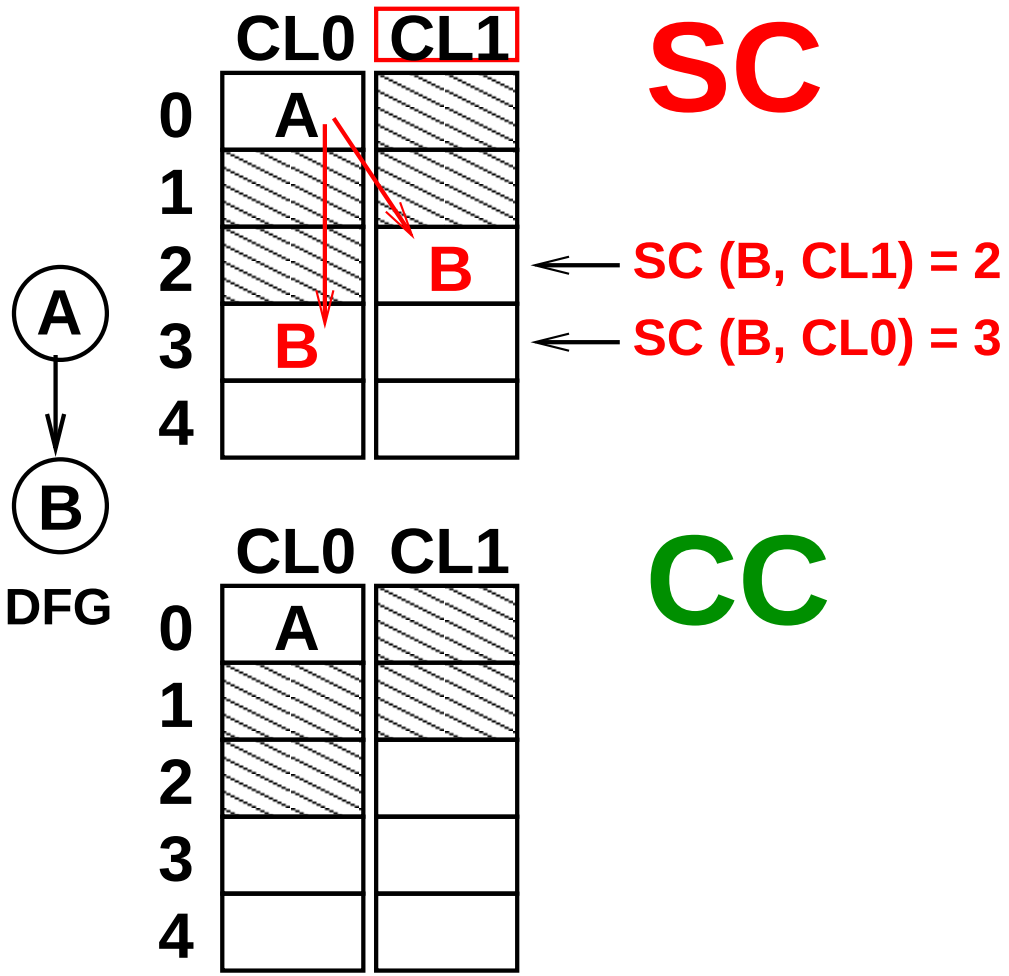

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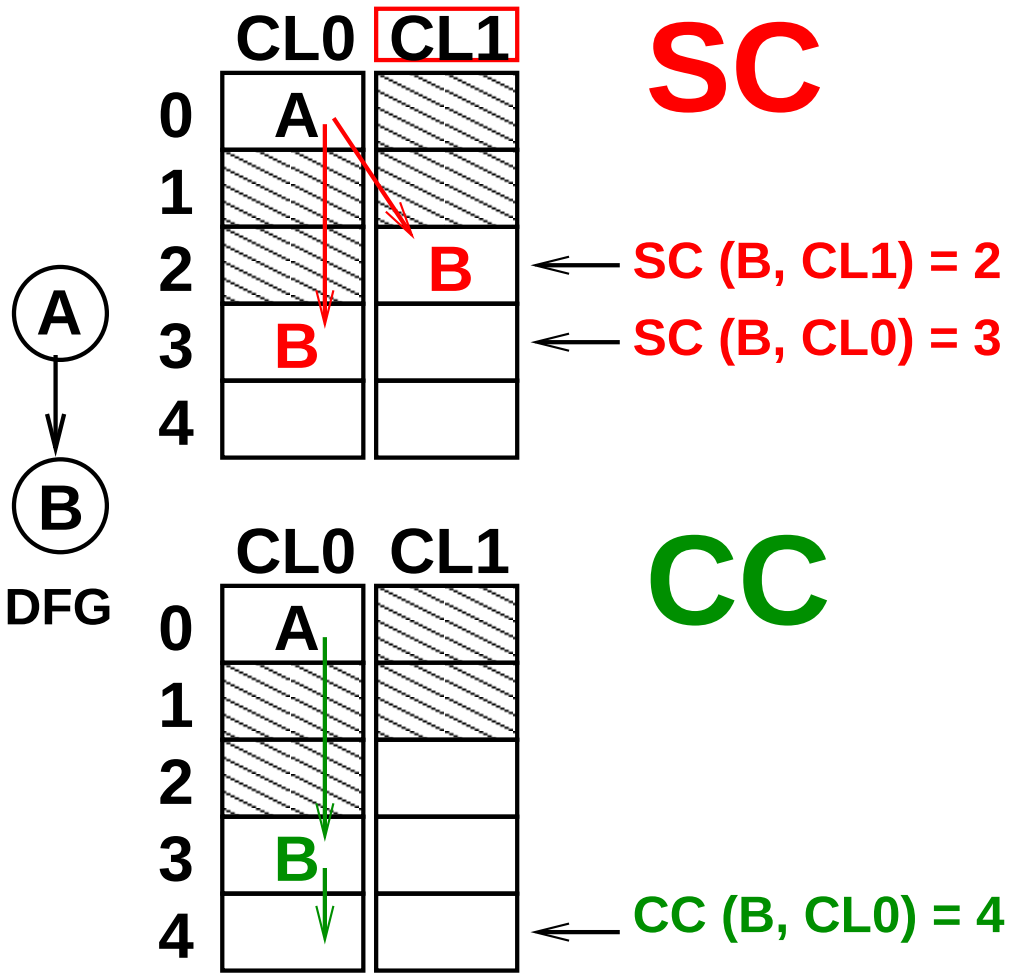

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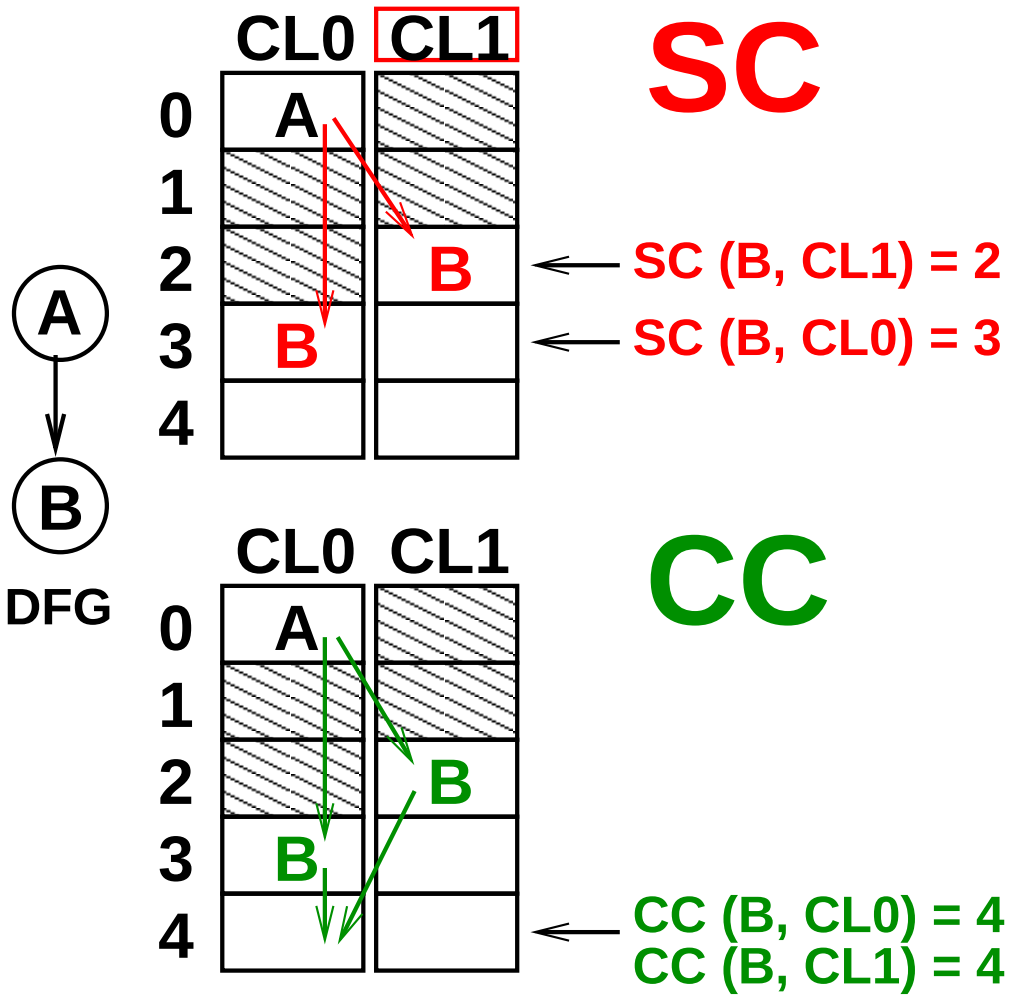

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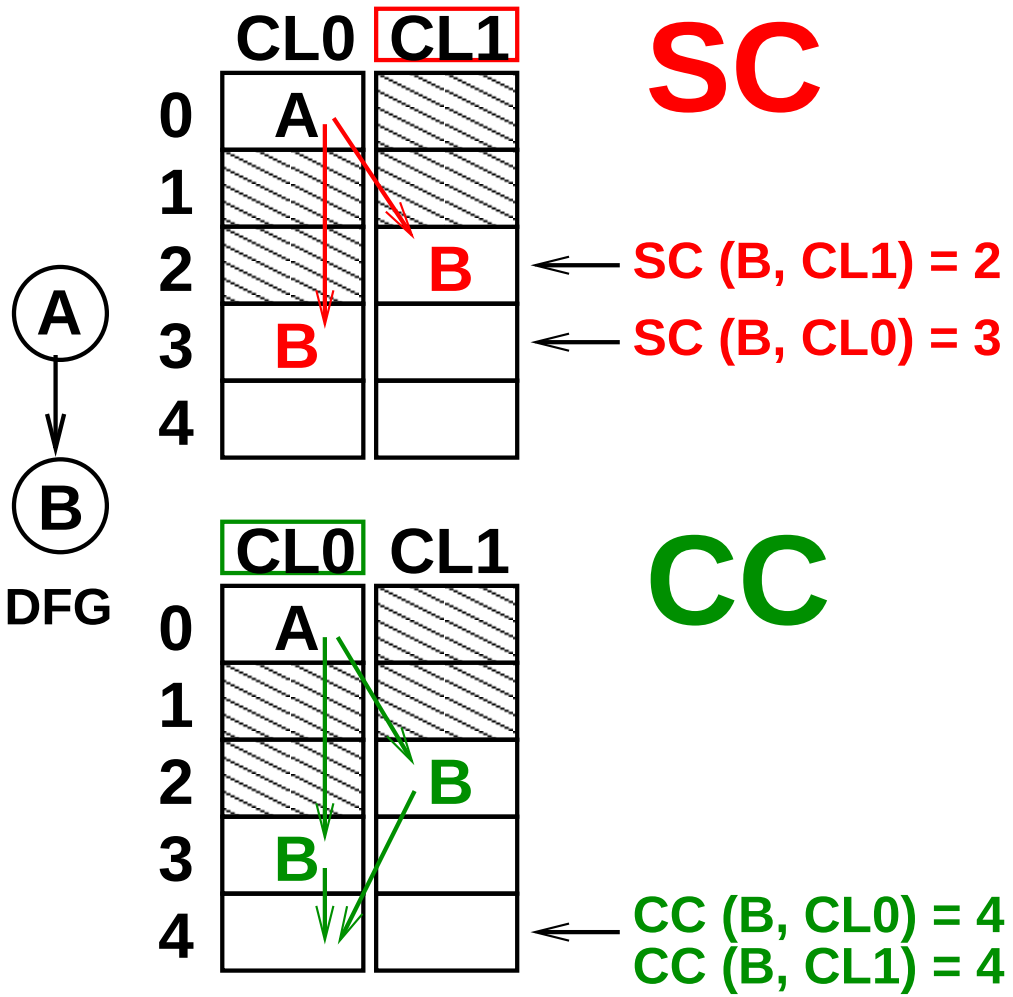
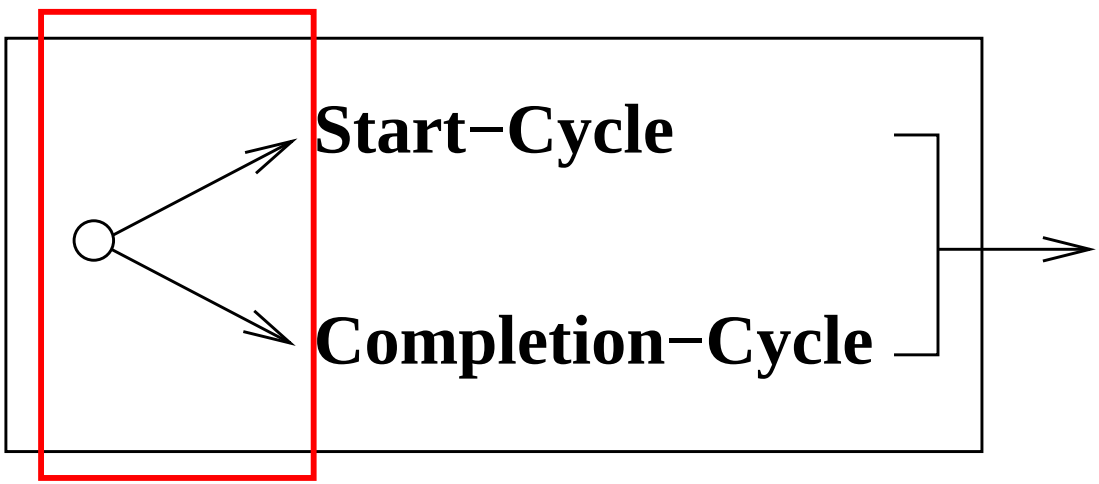
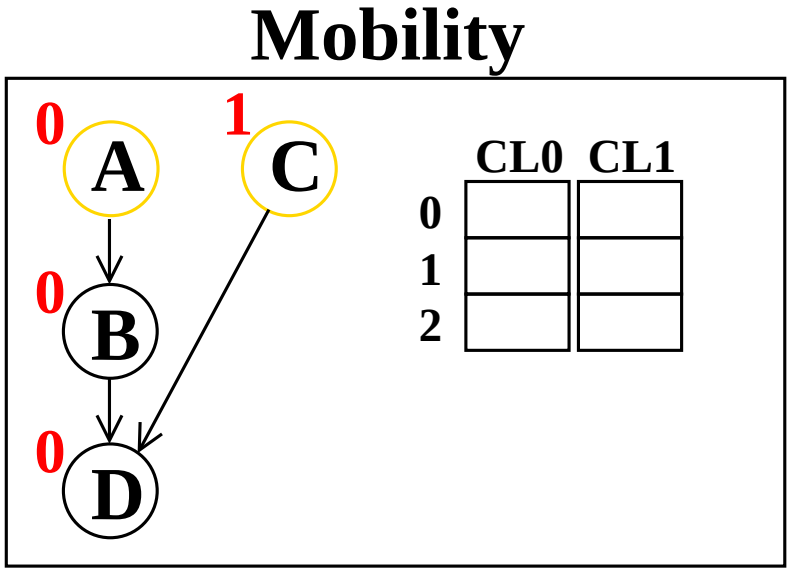


LUCAS switching heuristics



LUCAS switching heuristics - MOBILITY

- Mobility is a DFG-based heuristic.
- It measures the "slack" of an instruction in the DFG.
- If enough slack, cluster aggressively.



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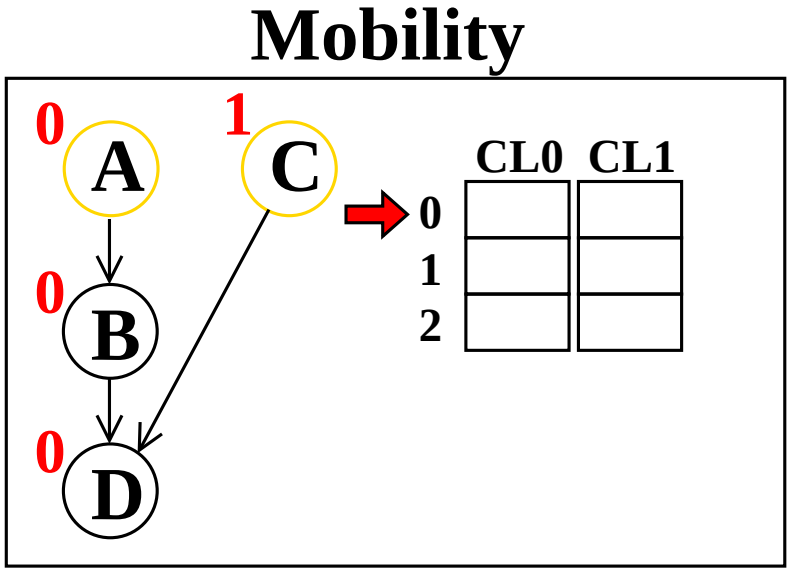

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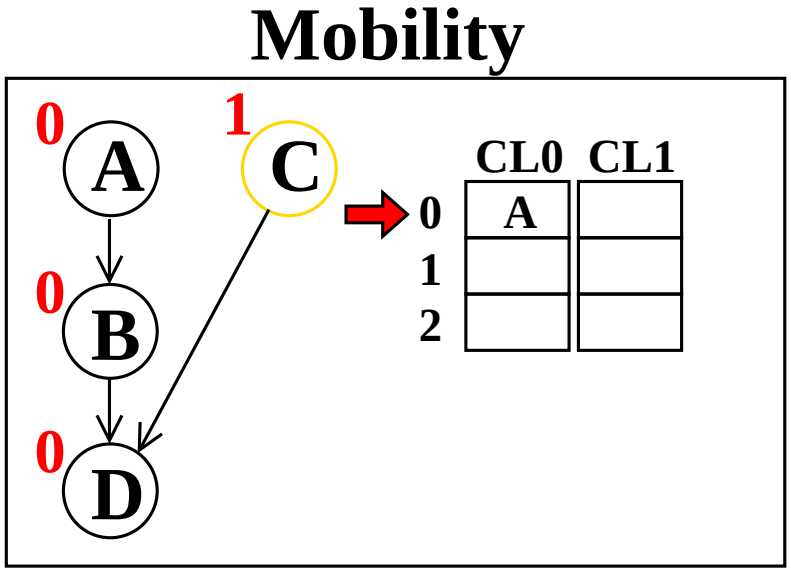

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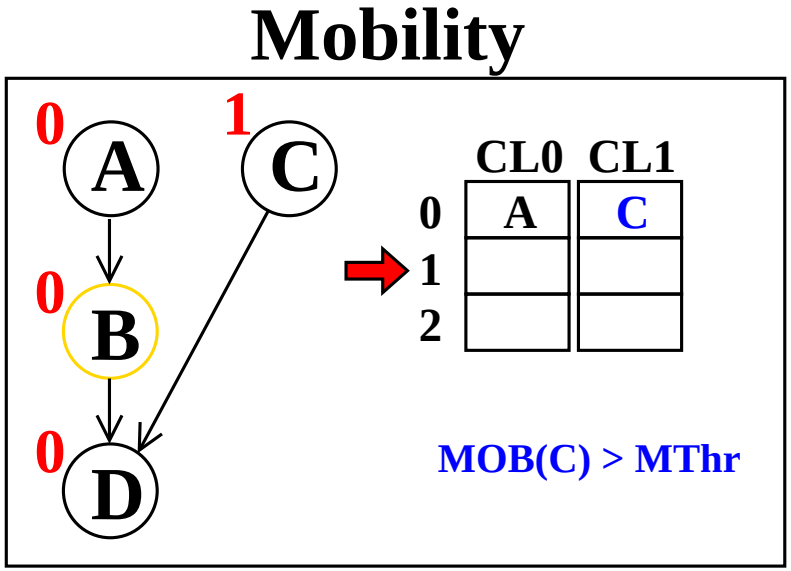

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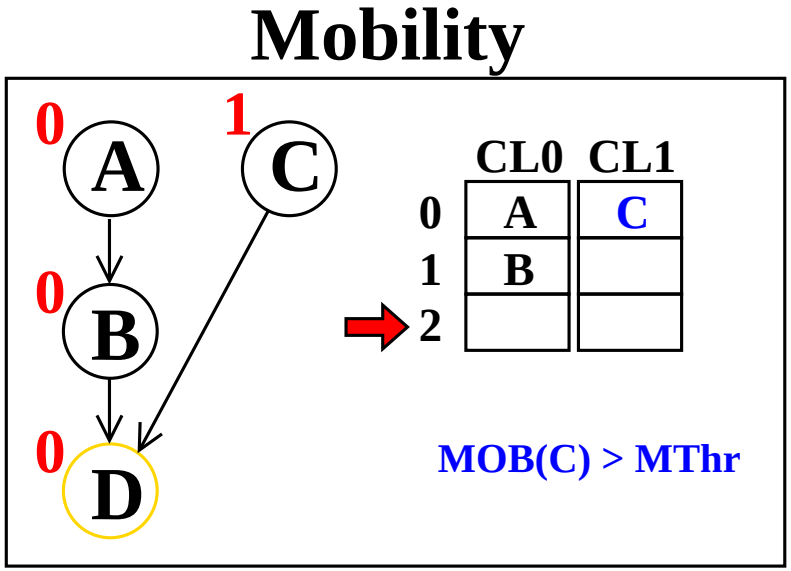

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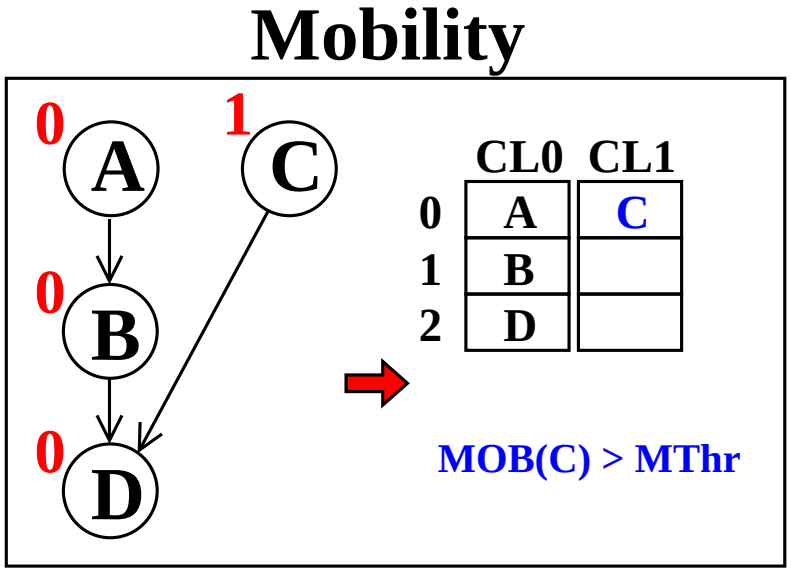

LUCAS switching heuristics - CONGESTION

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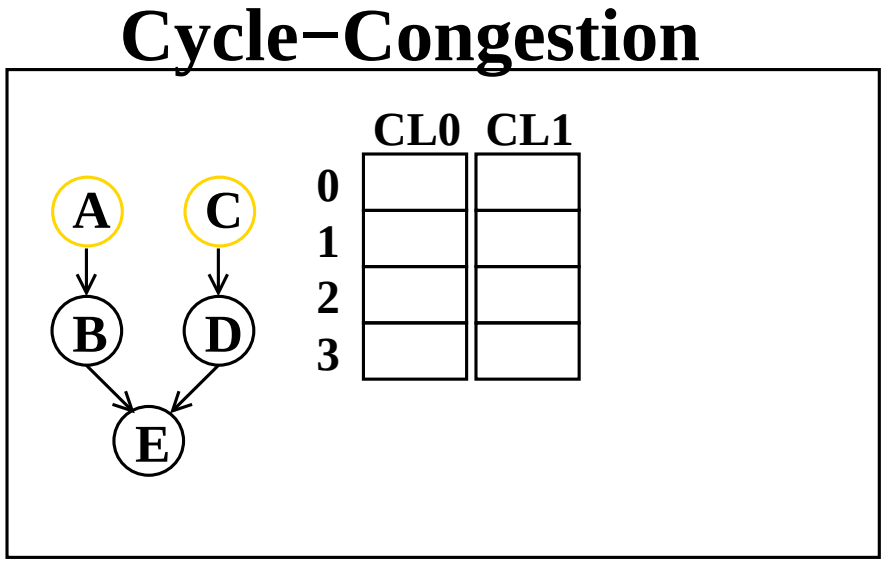
- If resources full, cluster aggressively.



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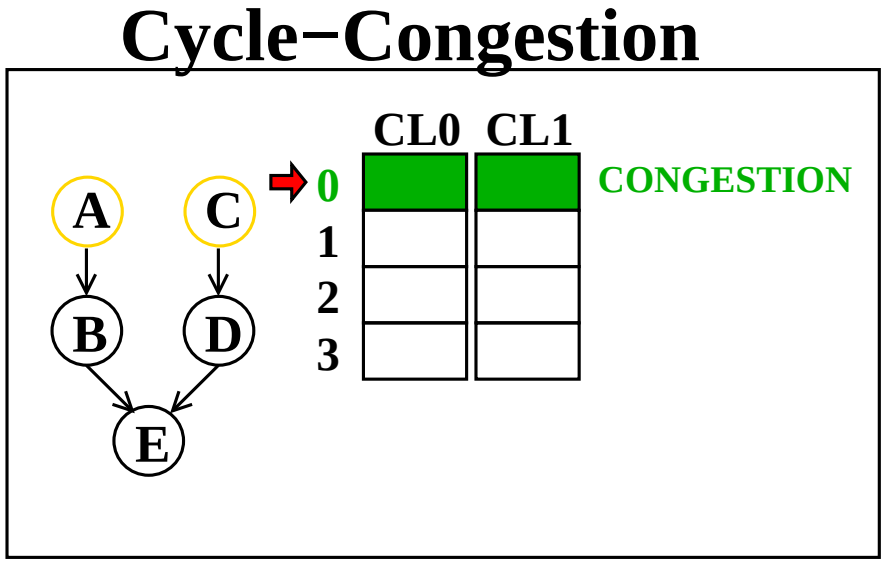

LUCAS switching heuristics - CONGESTION

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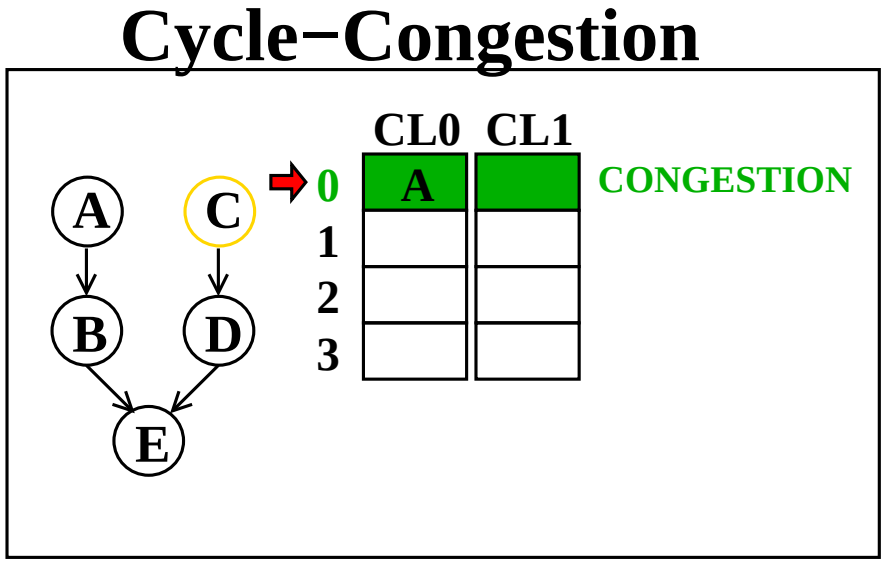

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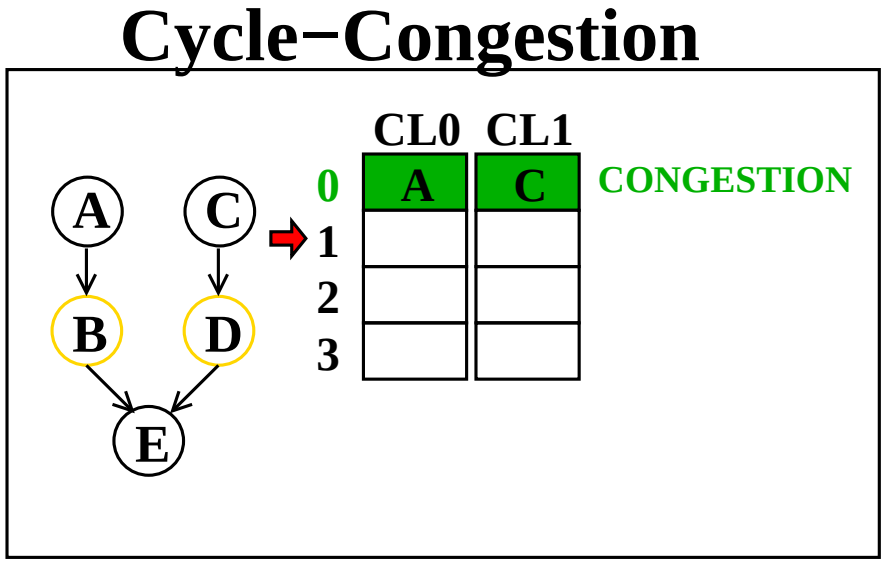

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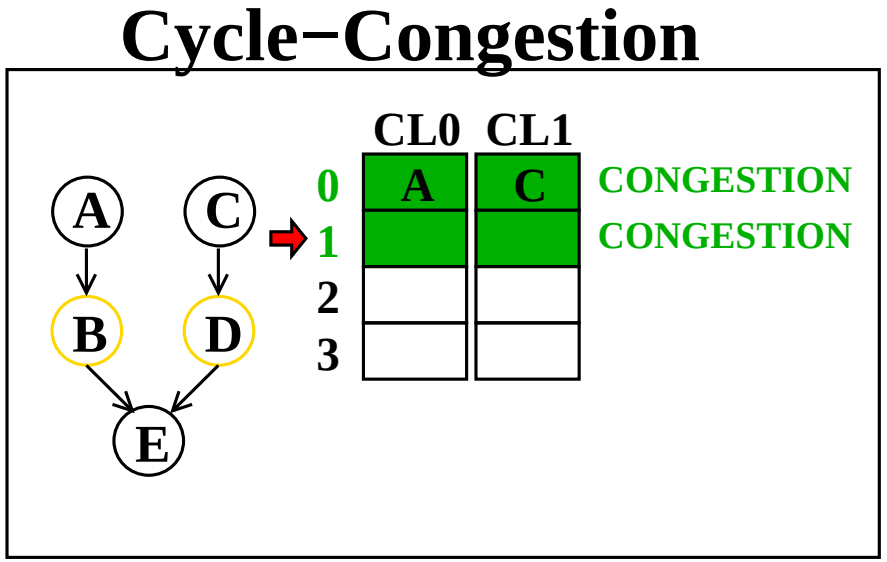

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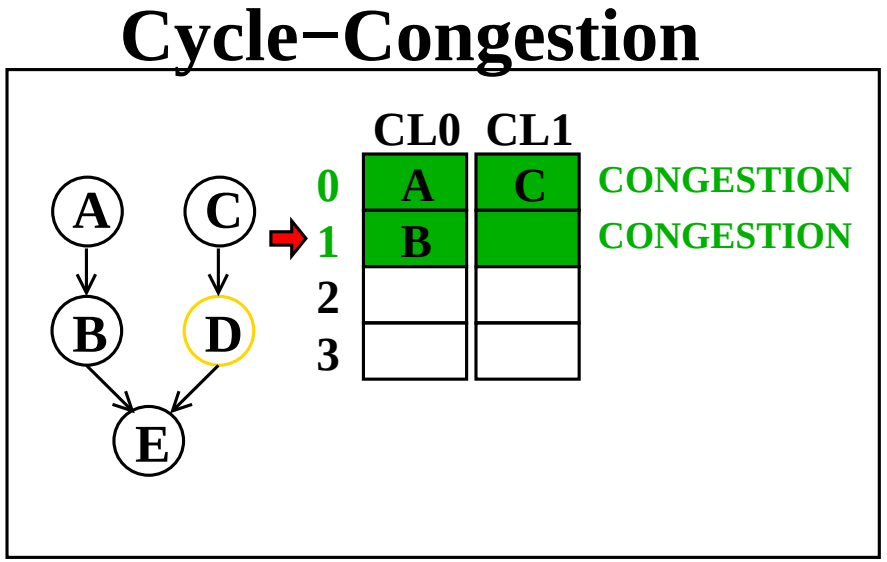

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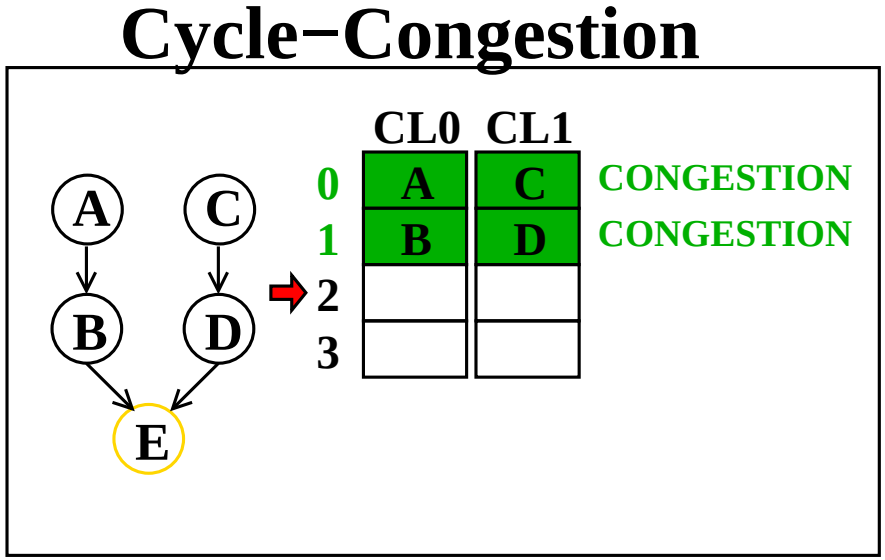

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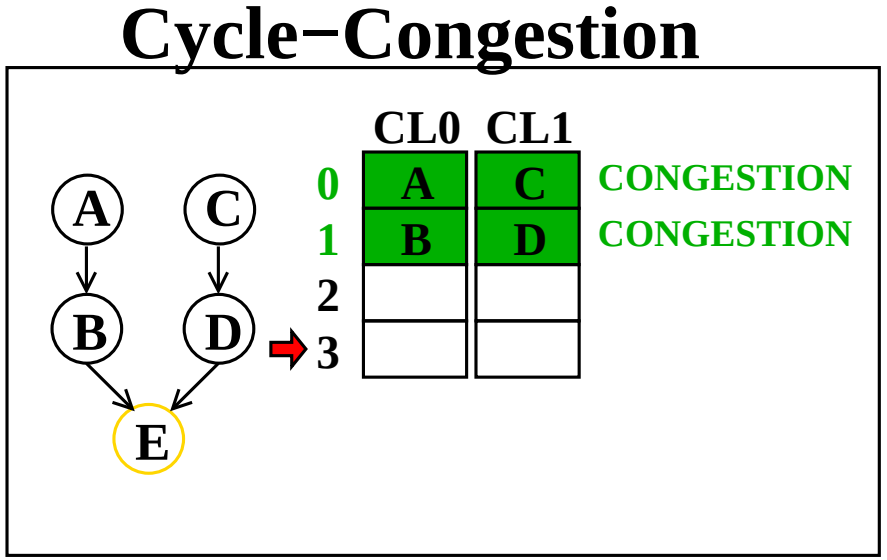

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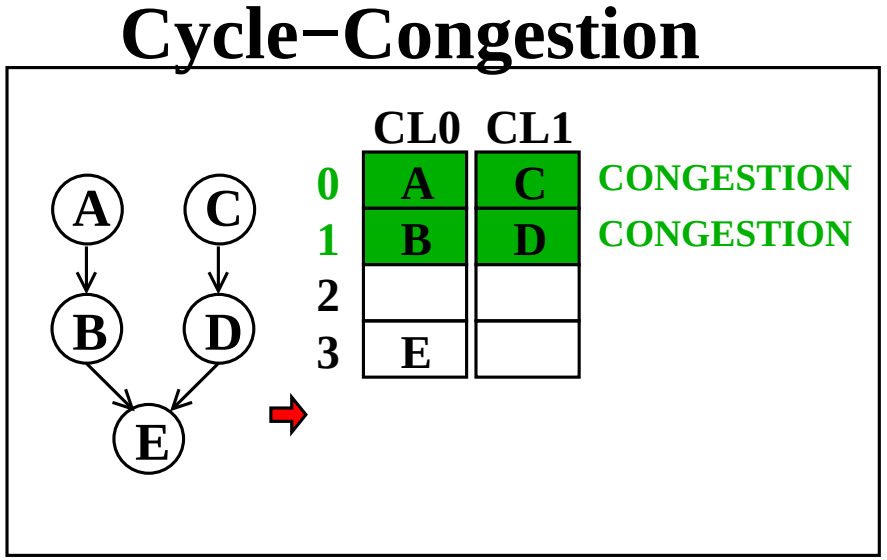
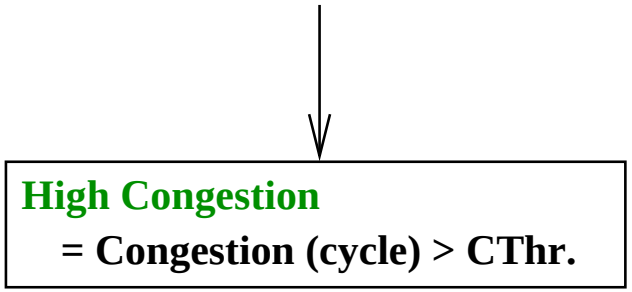
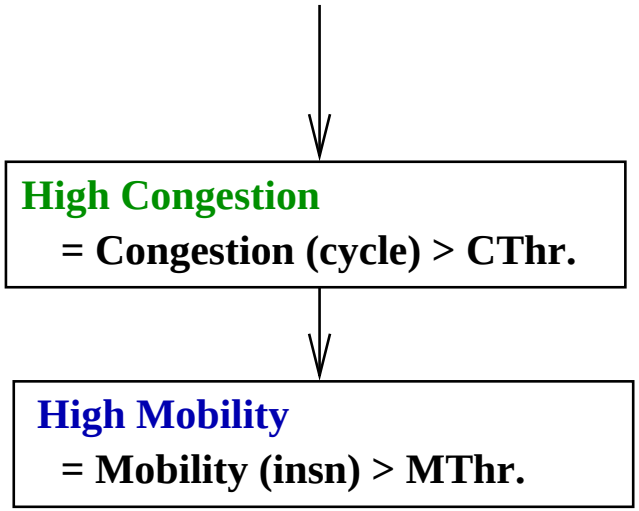


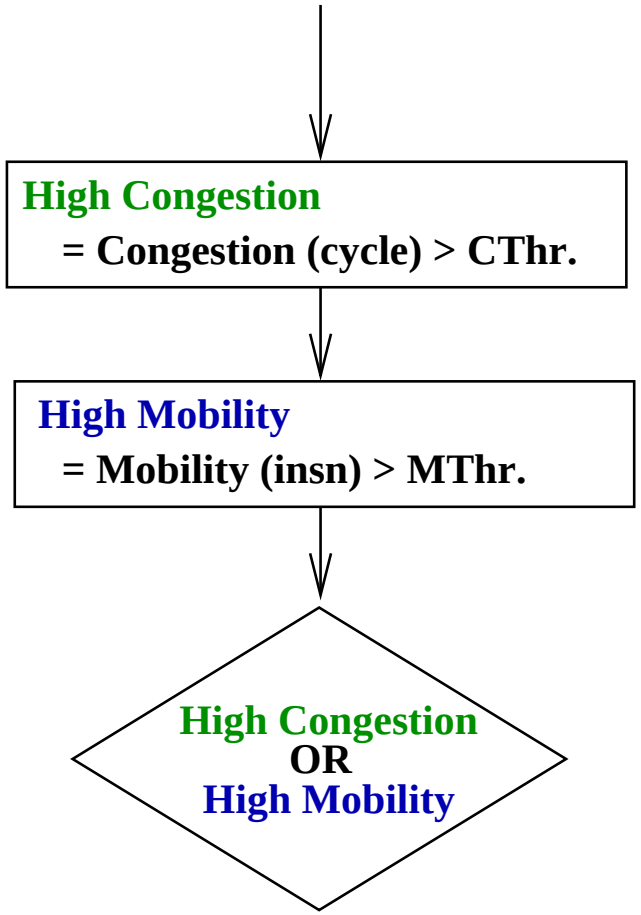
LUCAS Heuristic



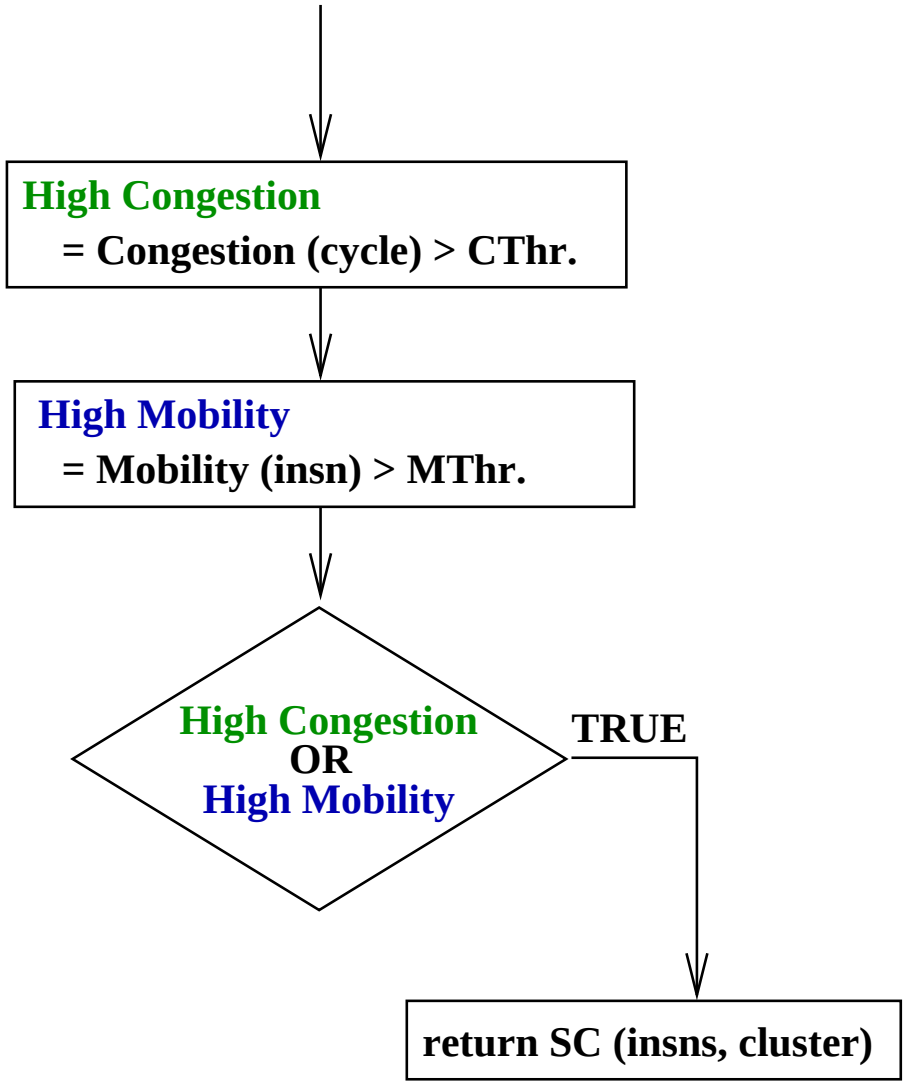
LUCAS Heuristic



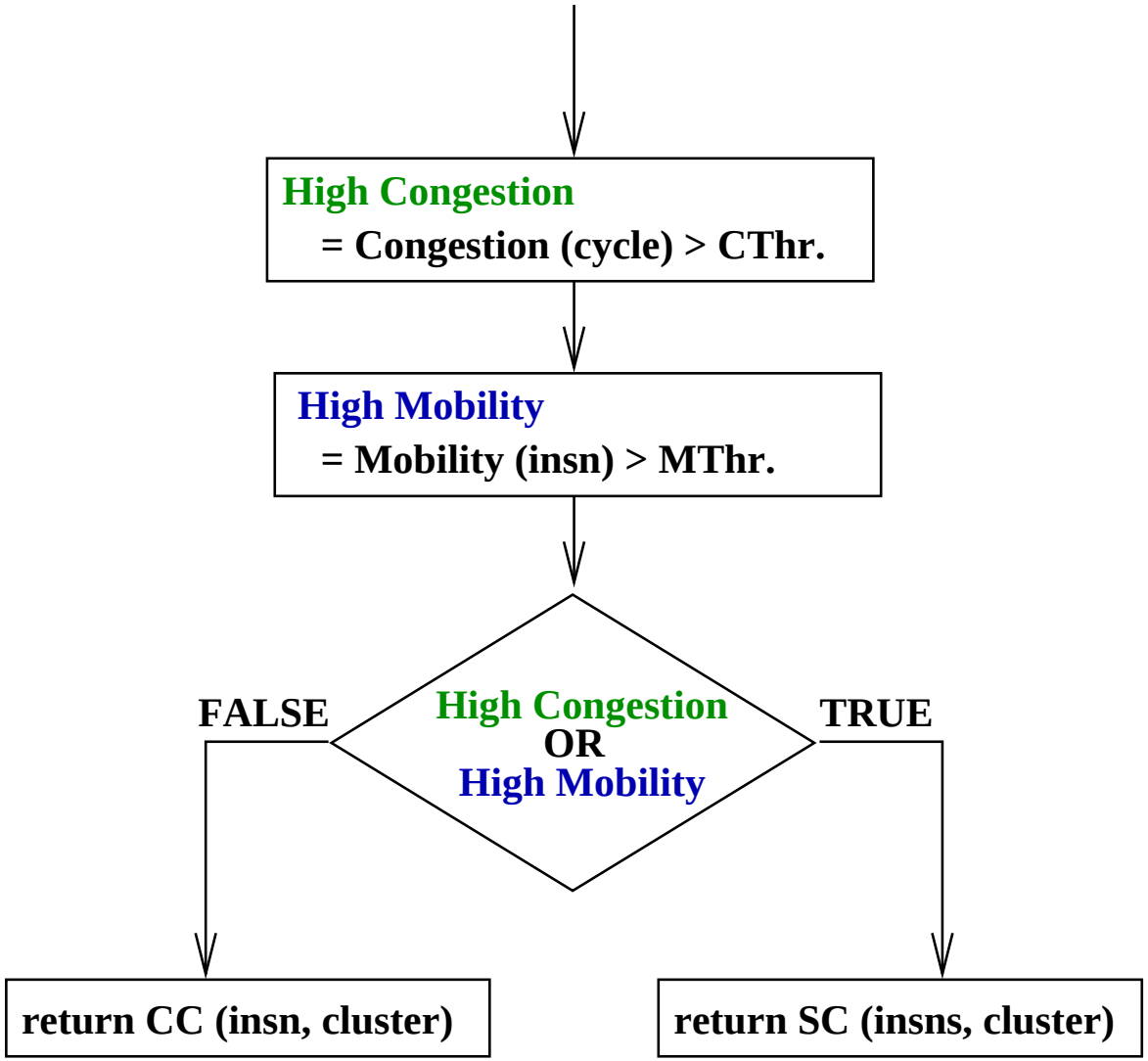
LUCAS Heuristic



LUCAS Heuristic



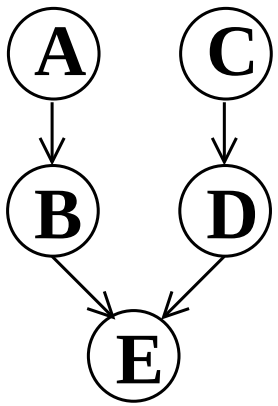
LUCAS Heuristic



Outline

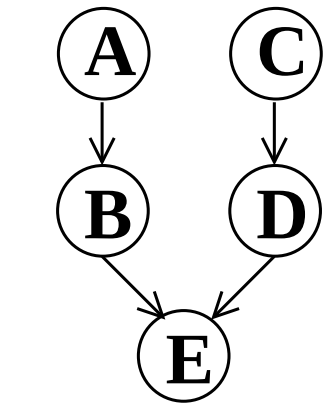
LUCAS Congestion Example

1 CYCLE **2 CYCLES** **3 CYCLES**



Data Flow Graph

LUCAS Congestion Example

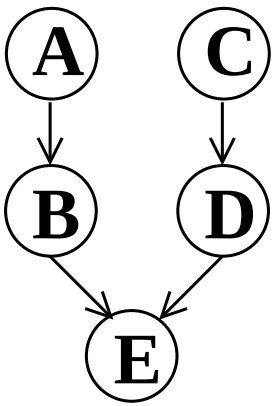


Data Flow Graph

SC

1 CYCLE 2 CYCLES 3 CYCLES

LUCAS Congestion Example



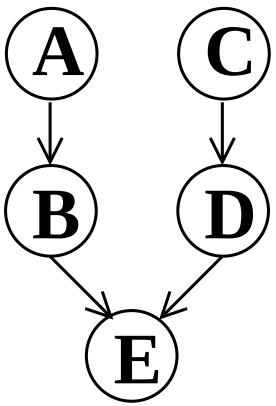
Data Flow Graph

1 CYCLE 2 CYCLES 3 CYCLES

SC

	CL0	CL1
0	A	C
1	B	D
2		
3	E	

LUCAS Congestion Example

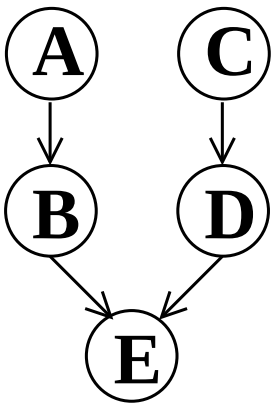


Data Flow Graph

SC

	1 CYCLE		2 CYCLES		3 CYCLES
	CL0	CL1	CL0	CL1	
0	A	C	A	C	
1	B	D	B	D	
2					
3	E				
			E		

LUCAS Congestion Example

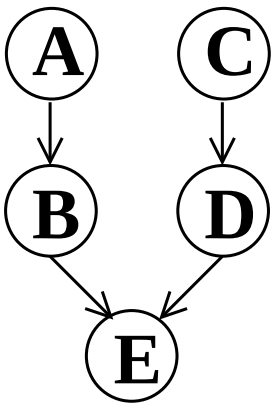


Data Flow Graph

SC

	1 CYCLE		2 CYCLES		3 CYCLES	
	CL0	CL1	CL0	CL1	CL0	CL1
0	A	C	A	C	A	C
1	B	D	B	D	B	D
2						
3	E					
			E		E	

LUCAS Congestion Example



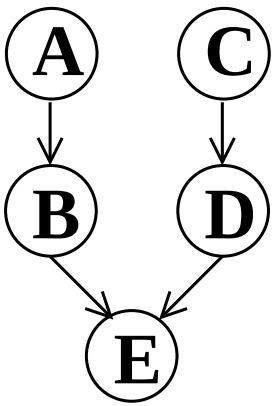
Data Flow Graph

SC

	1 CYCLE		2 CYCLES		3 CYCLES	
	CL0	CL1	CL0	CL1	CL0	CL1
0	A	C	A	C	A	C
1	B	D	B	D	B	D
2						
3	E					
			E			
					E	

CC

LUCAS Congestion Example



Data Flow Graph

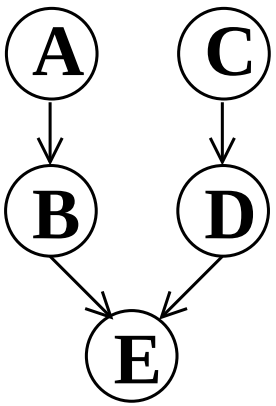
SC

	1 CYCLE CL0	1 CYCLE CL1	2 CYCLES CL0	2 CYCLES CL1	3 CYCLES CL0	3 CYCLES CL1
0	A	C	A	C	A	C
1	B	D	B	D	B	D
2						
3	E					
			E		E	

CC

0	A
1	C
2	B
3	D
4	E

LUCAS Congestion Example



Data Flow Graph

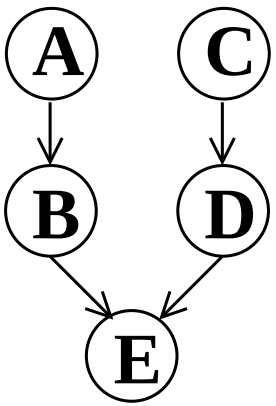
SC

	1 CYCLE CL0	1 CYCLE CL1	2 CYCLES CL0	2 CYCLES CL1	3 CYCLES CL0	3 CYCLES CL1
0	A	C	A	C	A	C
1	B	D	B	D	B	D
2						
3	E					
			E		E	

CC

	1 CYCLE		2 CYCLES	
0	A		A	
1	C		C	
2	B		B	
3	D		D	
4	E		E	

LUCAS Congestion Example



Data Flow Graph

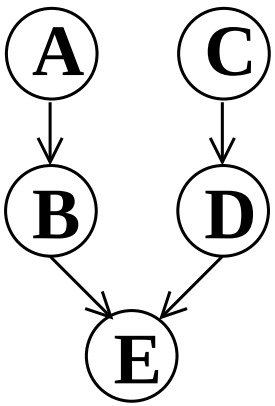
SC

	1 CYCLE		2 CYCLES		3 CYCLES	
	CL0	CL1	CL0	CL1	CL0	CL1
0	A	C	A	C	A	C
1	B	D	B	D	B	D
2						
3	E					
			E			
					E	

CC

0	A		A		A	
1	C		C		C	
2	B		B		B	
3	D		D		D	
4	E		E		E	

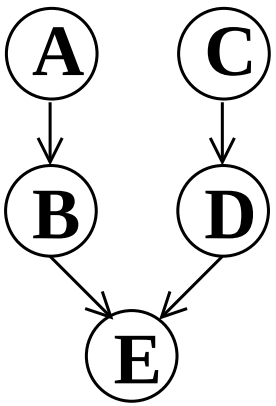
LUCAS Congestion Example



Data Flow Graph

	1 CYCLE		2 CYCLES		3 CYCLES	
	CL0	CL1	CL0	CL1	CL0	CL1
SC						
0	A	C	A	C	A	C
1	B	D	B	D	B	D
2						
3	E					
			E			
					E	
CC						
0	A		A		A	
1	C		C		C	
2	B		B		B	
3	D		D		D	
4	E		E		E	
LUCAS						

LUCAS Congestion Example

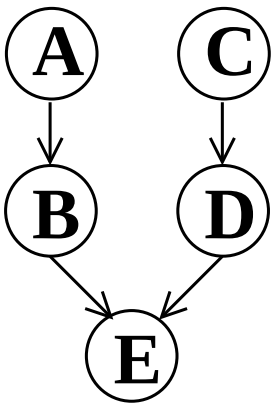


Data Flow Graph

	1 CYCLE		2 CYCLES		3 CYCLES	
	CL0	CL1	CL0	CL1	CL0	CL1
SC						
0	A	C	A	C	A	C
1	B	D	B	D	B	D
2						
3	E					
			E			
					E	
CC						
0	A		A		A	
1	C		C		C	
2	B		B		B	
3	D		D		D	
4	E		E		E	
LUCAS						
0	A	C				
1	B	D				
2						
3	E					

CONGESTION

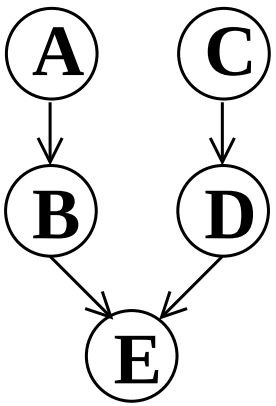
LUCAS Congestion Example



Data Flow Graph

	1 CYCLE		2 CYCLES		3 CYCLES	
	CL0	CL1	CL0	CL1	CL0	CL1
SC						
0	A	C	A	C	A	C
1	B	D	B	D	B	D
2						
3	E					
			E			
					E	
CC						
0	A		A		A	
1	C		C		C	
2	B		B		B	
3	D		D		D	
4	E		E		E	
LUCAS						
0	A	C	A	C		
1	B	D	B	D		
2						
3	E					
	CONGESTION					
			E			

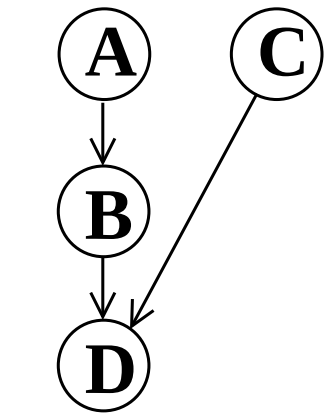
LUCAS Congestion Example



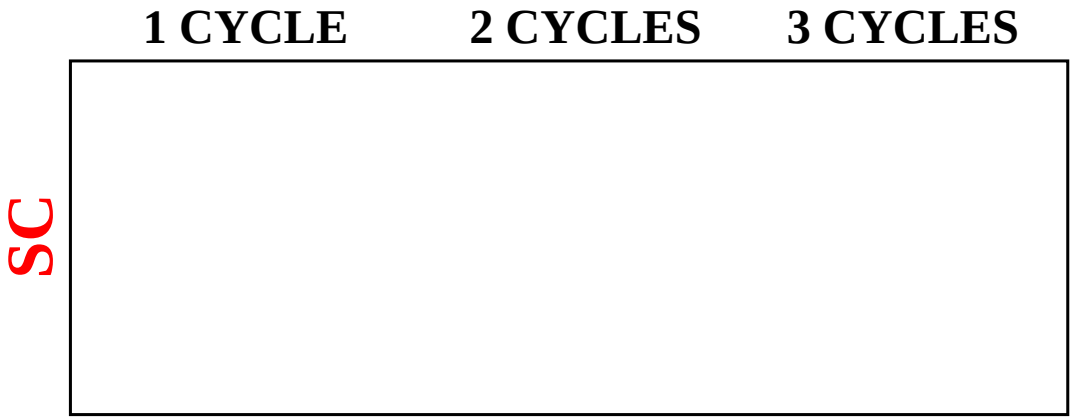
Data Flow Graph

	1 CYCLE		2 CYCLES		3 CYCLES	
	CL0	CL1	CL0	CL1	CL0	CL1
SC						
0	A	C	A	C	A	C
1	B	D	B	D	B	D
2						
3	E					
			E			
					E	
CC						
0	A		A		A	
1	C		C		C	
2	B		B		B	
3	D		D		D	
4	E		E		E	
LUCAS						
0	A	C	A	C	A	
1	B	D	B	D	C	
2					B	
3	E				D	
	CONGESTION		E		E	

LUCAS Mobility Example



Data Flow Graph



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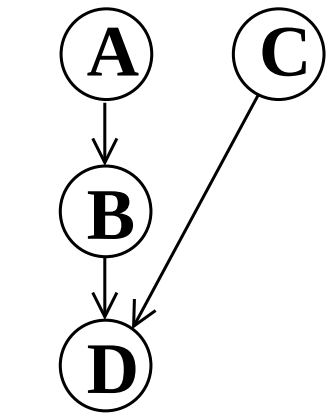


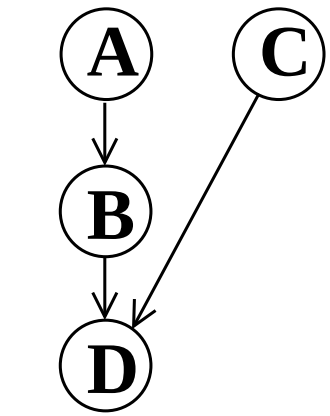
Data Flow Graph

1 CYCLE 2 CYCLES 3 CYCLES

SC

	CL0	CL1
0	A	C
1	B	
2	D	

LUCAS Mobility Example

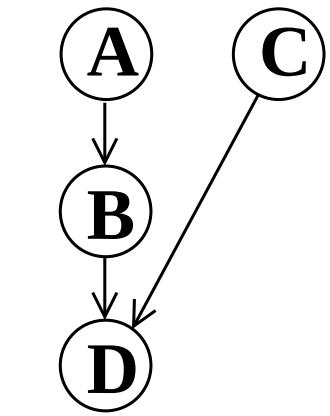


Data Flow Graph

SC

	1 CYCLE		2 CYCLES	
	CL0	CL1	CL0	CL1
0	A	C	A	C
1	B		B	
2	D			
			D	

LUCAS Mobility Example

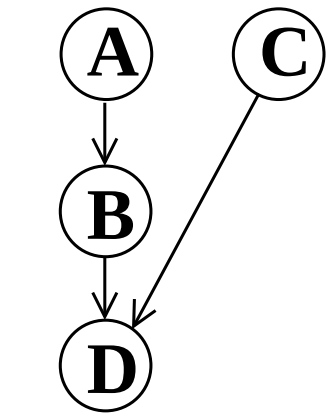


Data Flow Graph

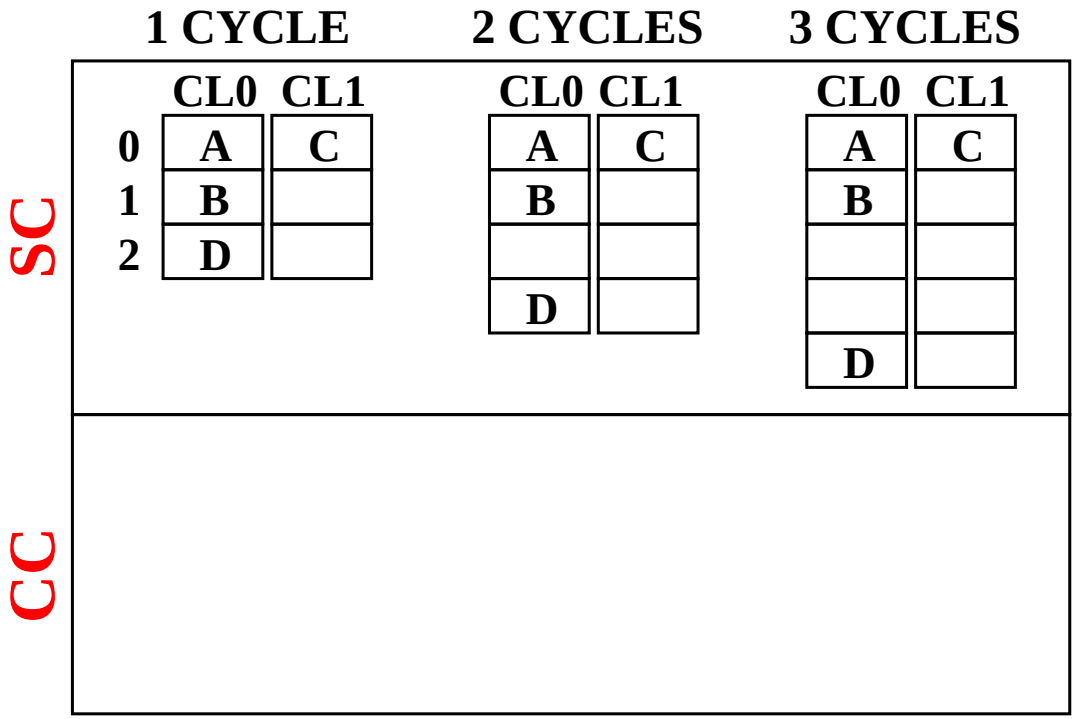
SC

	1 CYCLE		2 CYCLES		3 CYCLES	
	CL0	CL1	CL0	CL1	CL0	CL1
0	A	C	A	C	A	C
1	B		B		B	
2	D					
			D			
					D	

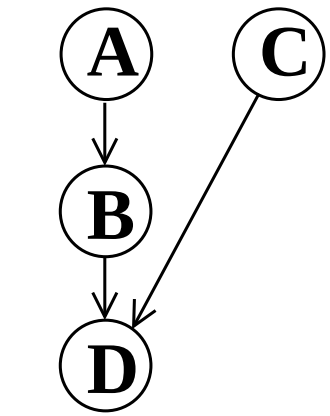
LUCAS Mobility Example



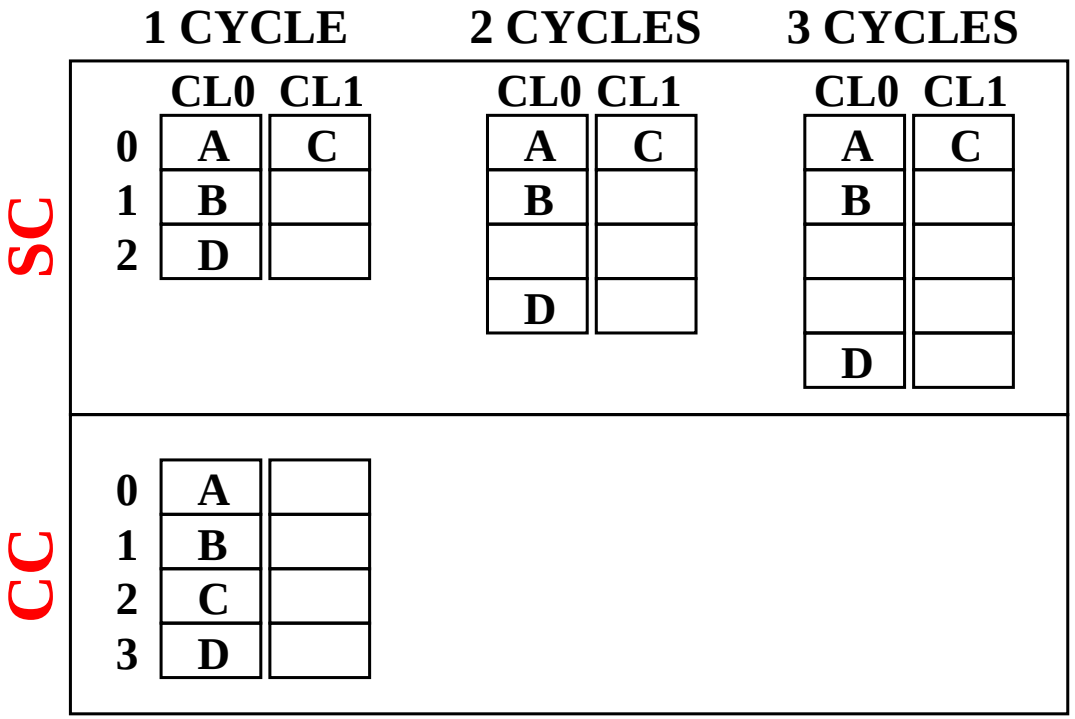
Data Flow Graph



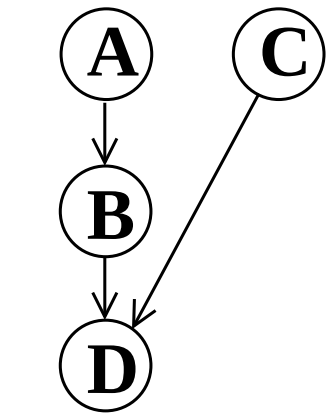
LUCAS Mobility Example



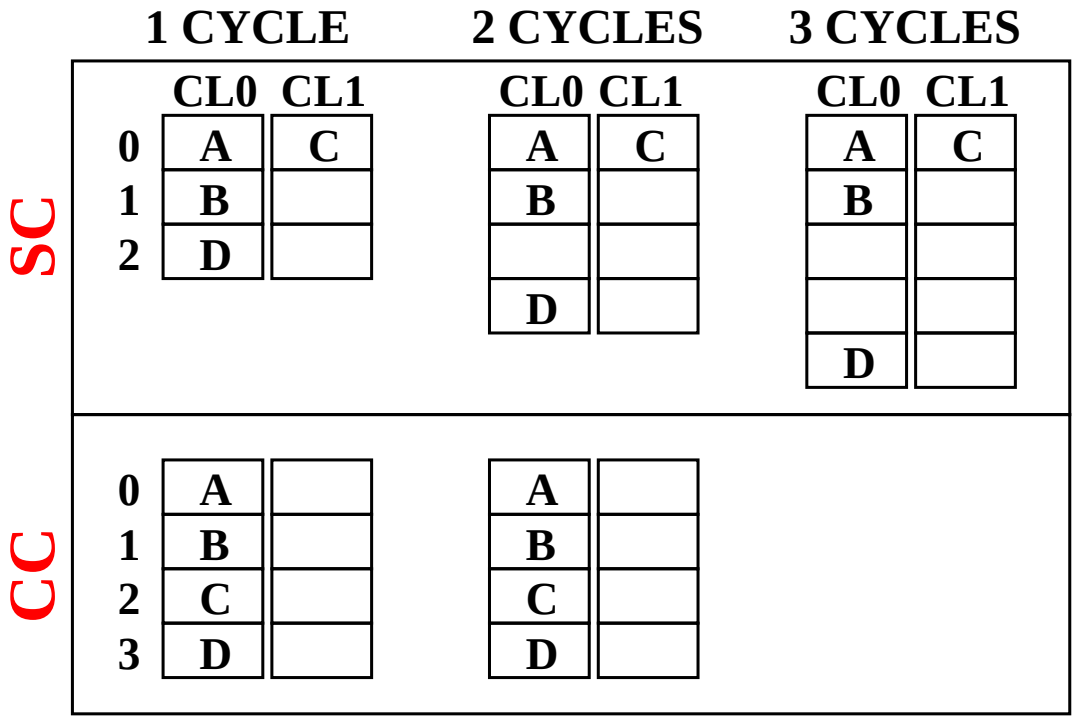
Data Flow Graph



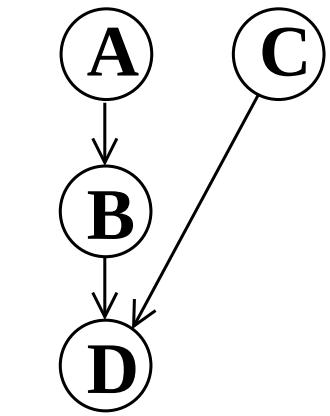
LUCAS Mobility Example



Data Flow Graph



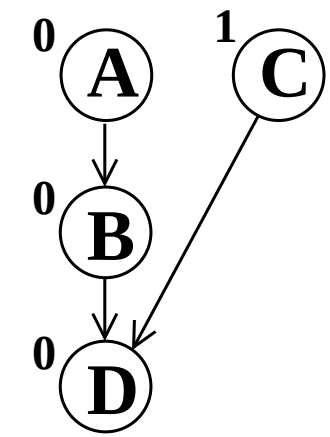
LUCAS Mobility Example



Data Flow Graph

	1 CYCLE		2 CYCLES		3 CYCLES	
SC	CL0	CL1	CL0	CL1	CL0	CL1
0	A	C	A	C	A	C
1	B		B		B	
2	D					
			D			
					D	
CC						
0	A		A		A	
1	B		B		B	
2	C		C		C	
3	D		D		D	

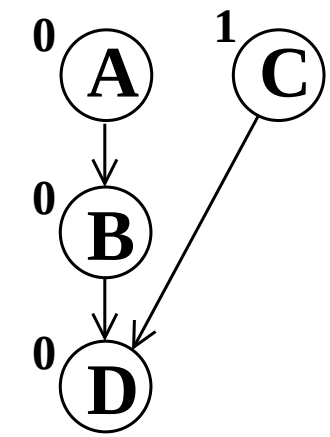
LUCAS Mobility Example



Data Flow Graph

	1 CYCLE		2 CYCLES		3 CYCLES	
	CL0	CL1	CL0	CL1	CL0	CL1
SC						
0	A	C	A	C	A	C
1	B		B		B	
2	D					
			D			
					D	
CC						
0	A		A		A	
1	B		B		B	
2	C		C		C	
3	D		D		D	
LUCAS						

LUCAS Mobility Example

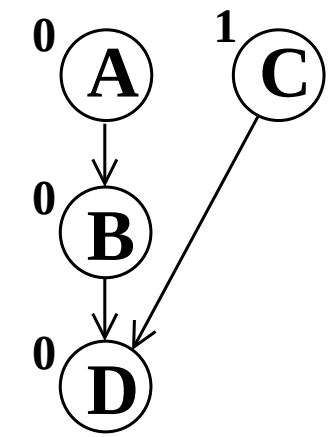


Data Flow Graph

		1 CYCLE		2 CYCLES		3 CYCLES	
		CL0	CL1	CL0	CL1	CL0	CL1
SC	0	A	C	A	C	A	C
	1	B		B		B	
	2	D					
				D			
						D	
CC	0	A		A		A	
	1	B		B		B	
	2	C		C		C	
	3	D		D		D	
LUCAS	0	A	C				
	1	B					
	2	D					

MOB(C) > MThr

LUCAS Mobility Example



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				D			
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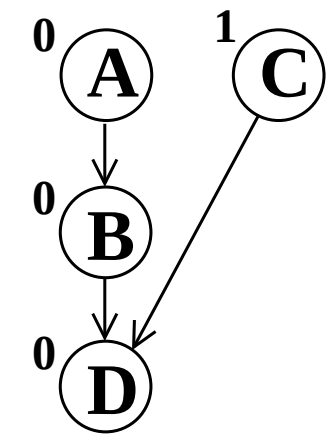

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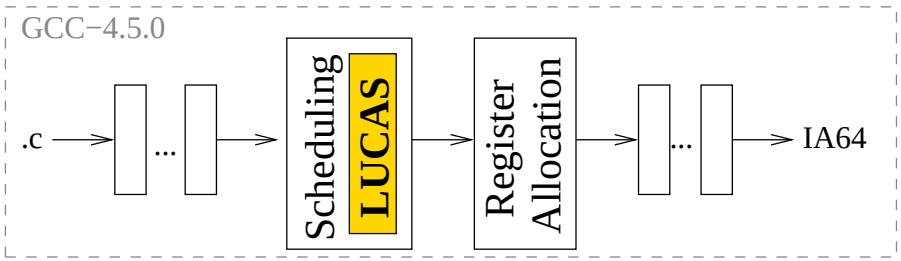
Outline

Experimental Setup

- Compiler: GCC-4.5.0, Modified Haifa-Scheduler



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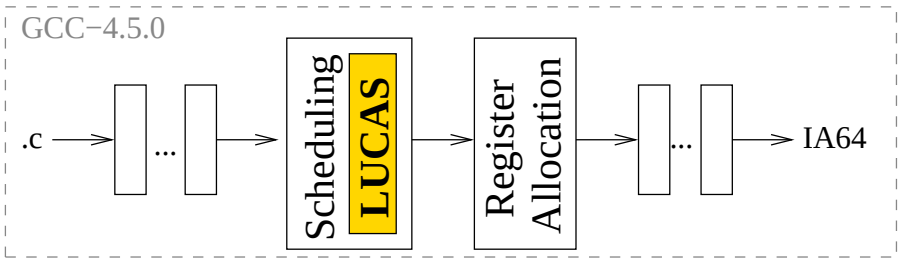

- Architecture
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  - Modified SKI IA64 simulator

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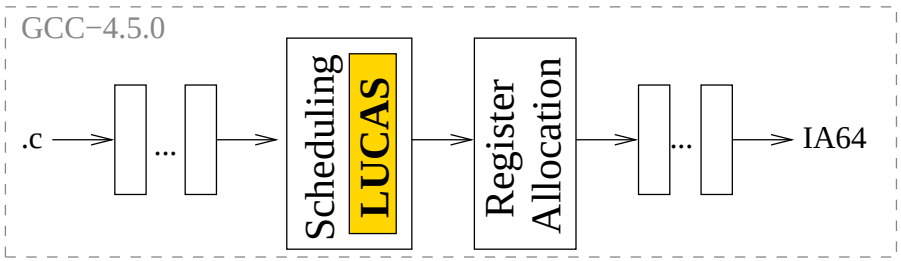

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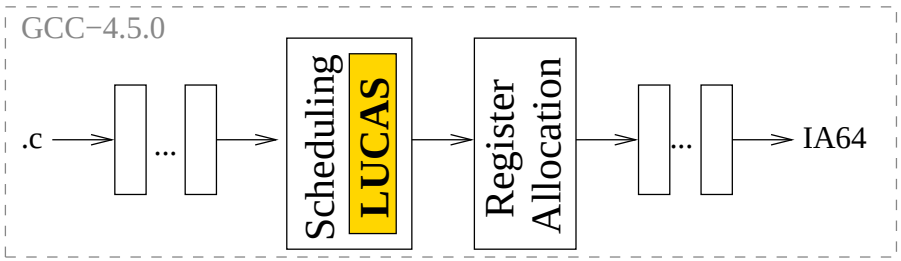

- Architecture
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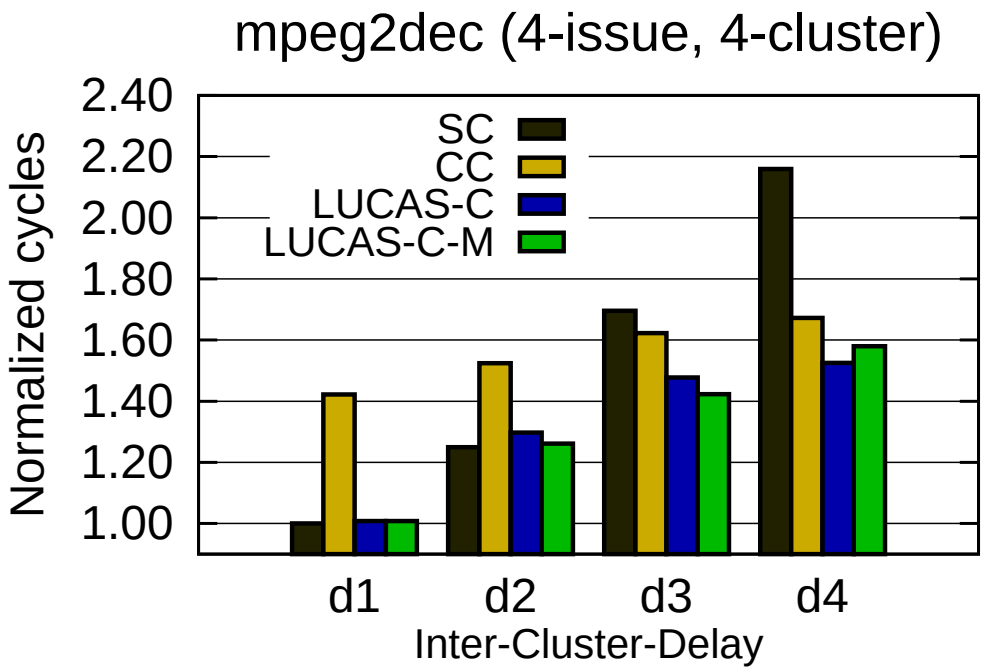
- Benchmarks: MediabenchII Video Benchmark suite
- Compare:
  - Start-Cycle (SC), Completion-Cycle (CC), LUCAS with Congestion (LUCAS-C) and Mobility (LUCAS-C-M)
  - For comparisons against UAS and Critical-Successor (CS), please refer to the paper.

Performance Comparison



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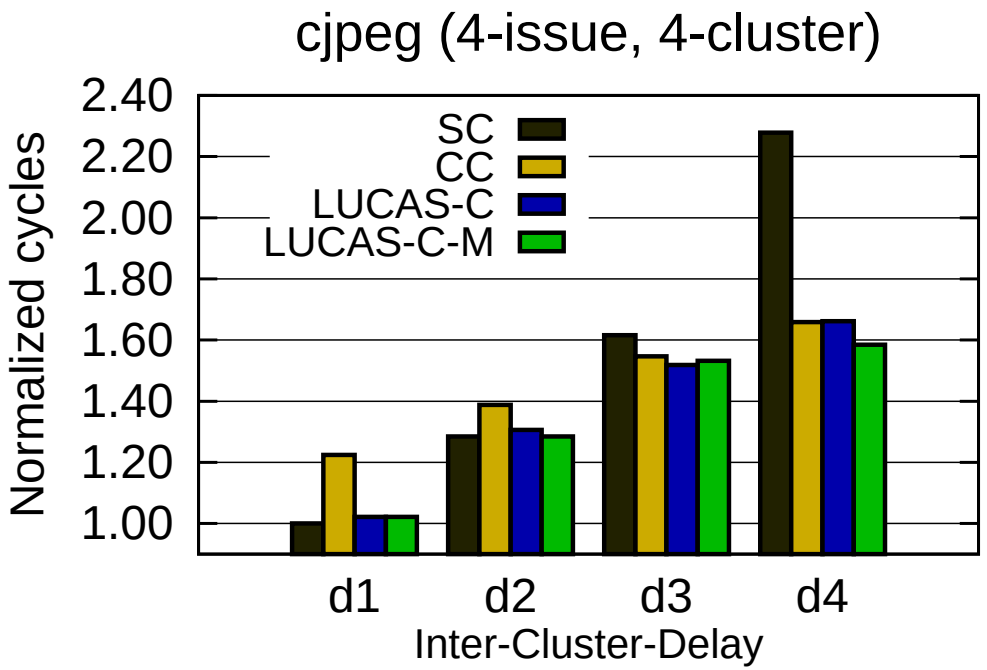
- Match CC at high delays
- Often outperform best due to fine-grain switching

Performance Comparison



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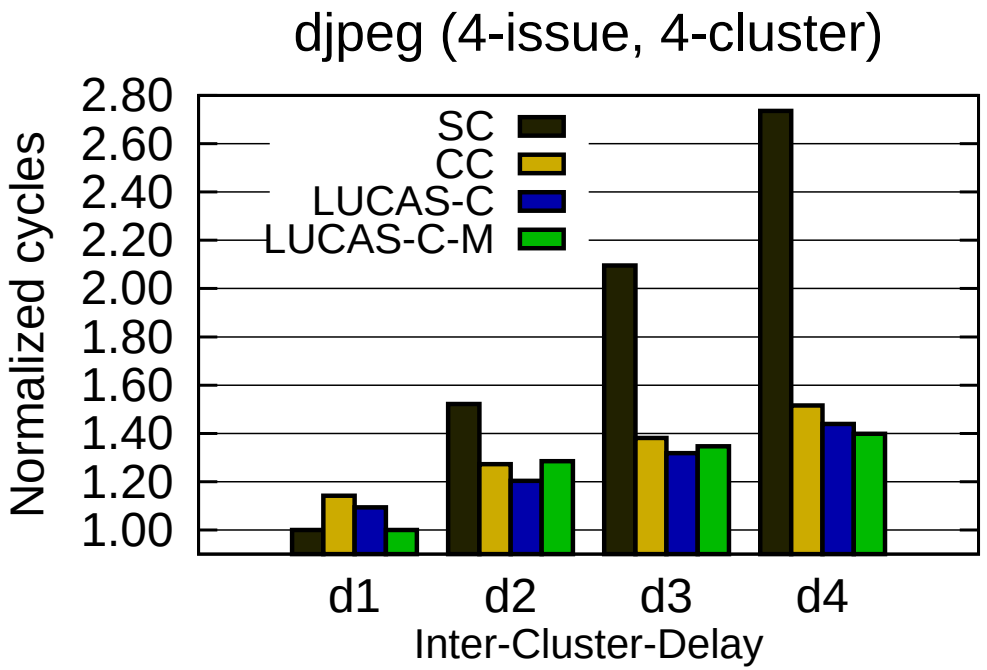

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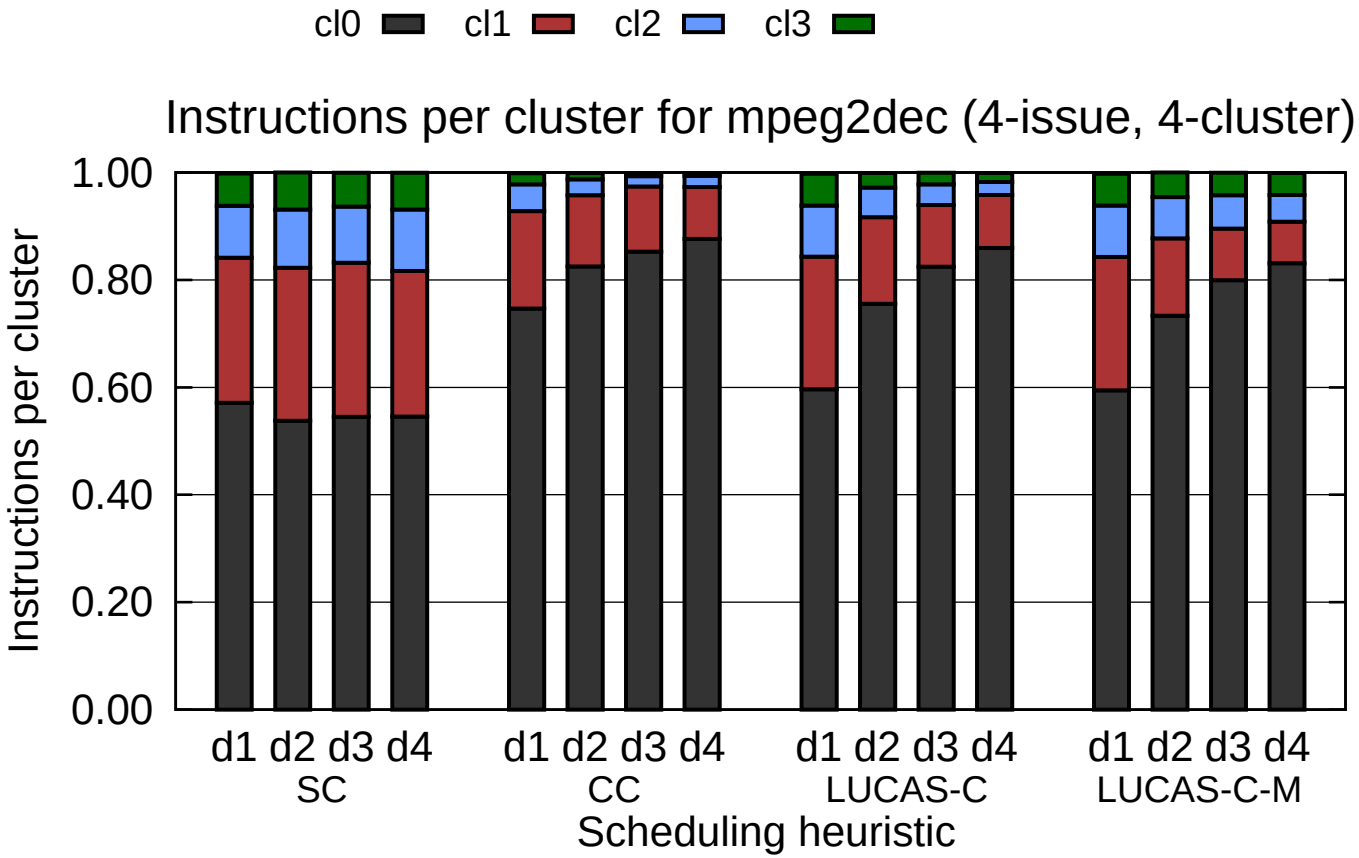
Instruction Distribution



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- Less aggressive at high delays

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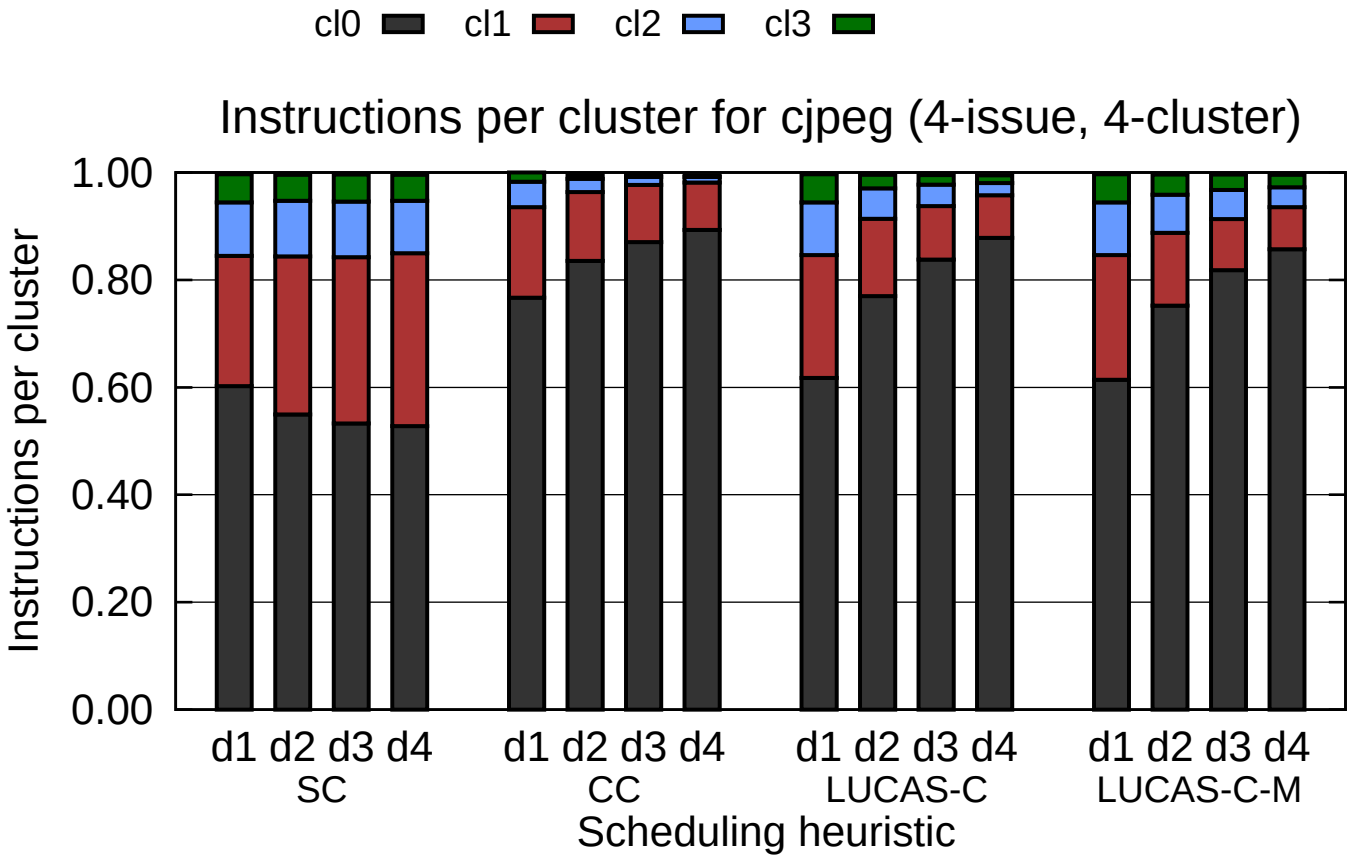

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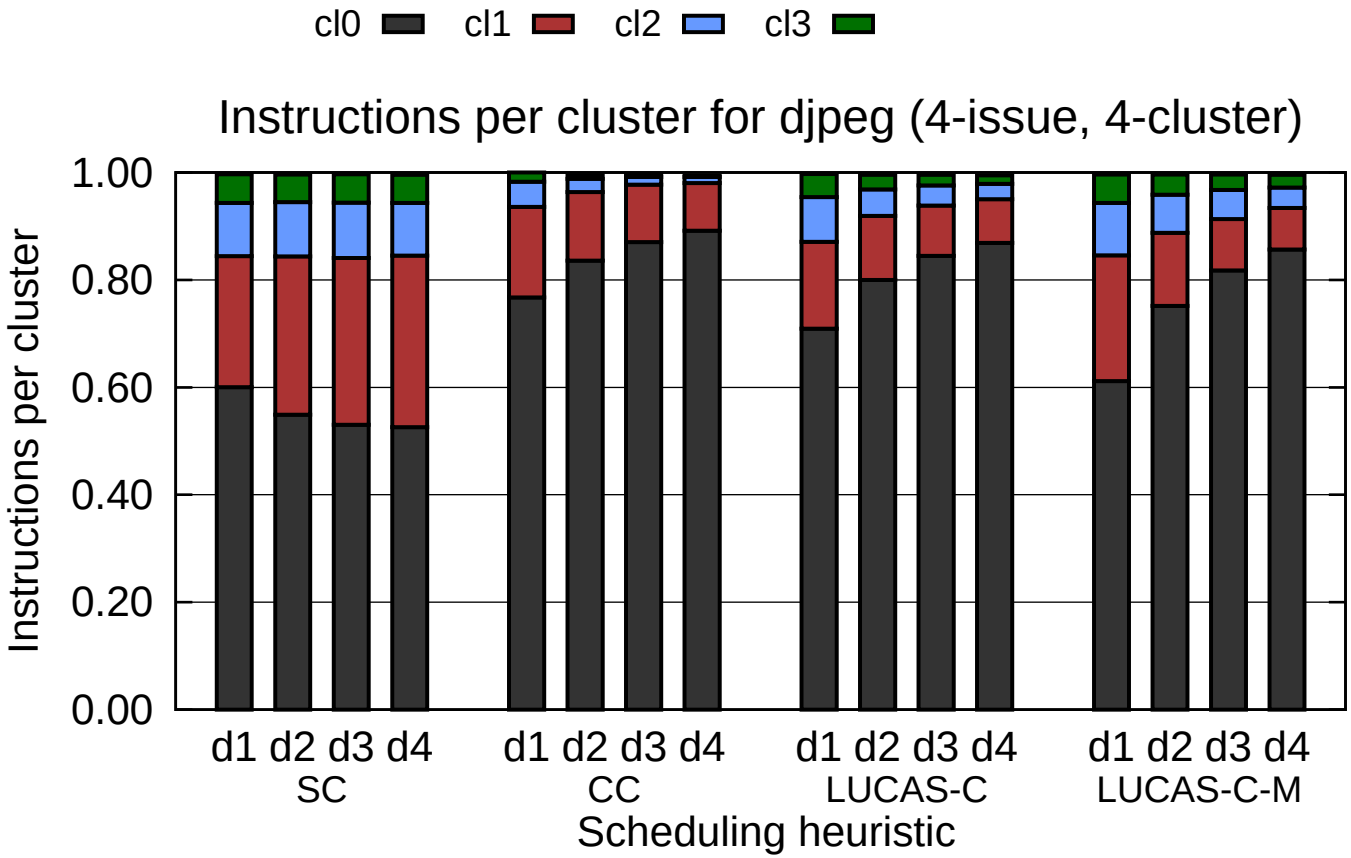


- LUCAS: Aggressive distribution at small delays.
- Less aggressive at high delays
- Similar results in most benchmarks

Conclusion

Proposed LUCAS, a Latency-Adaptive scheduler for clustered VLIWs that:

- Performs unified cluster assignment and instruction scheduling
- Generates fast code no matter the inter-cluster delay
- Often outperforms the best of the state-of-the-art due to fine-grain switching between heuristics.

LUCAS: Latency-adaptive Unified Cluster Assignment and instruction Scheduling

Vasileios Porpodas and Marcelo Cintra

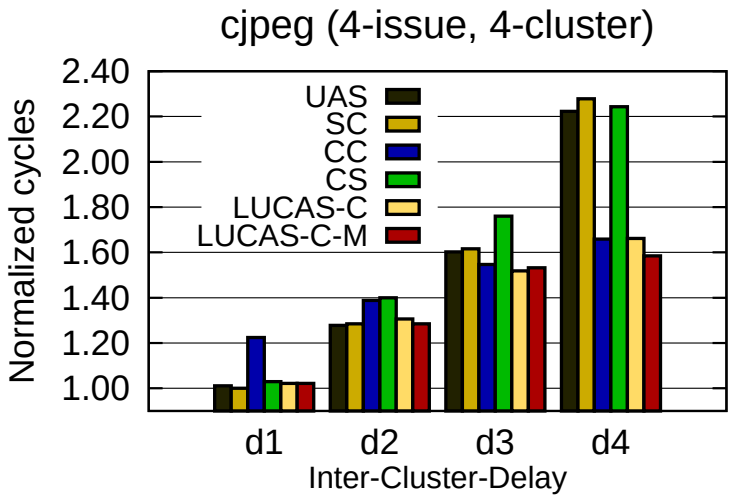
University of Edinburgh

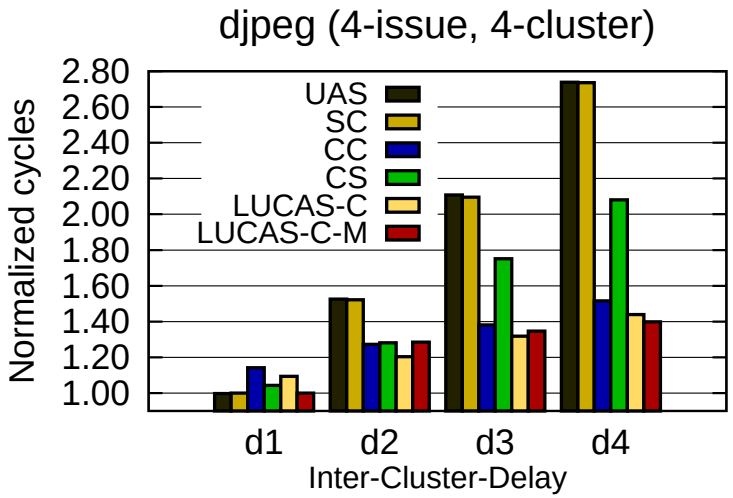
LCTES 2013

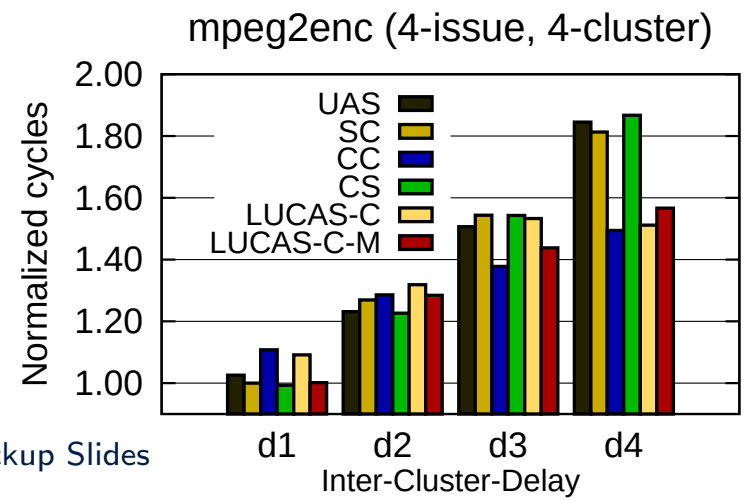
Backup slides

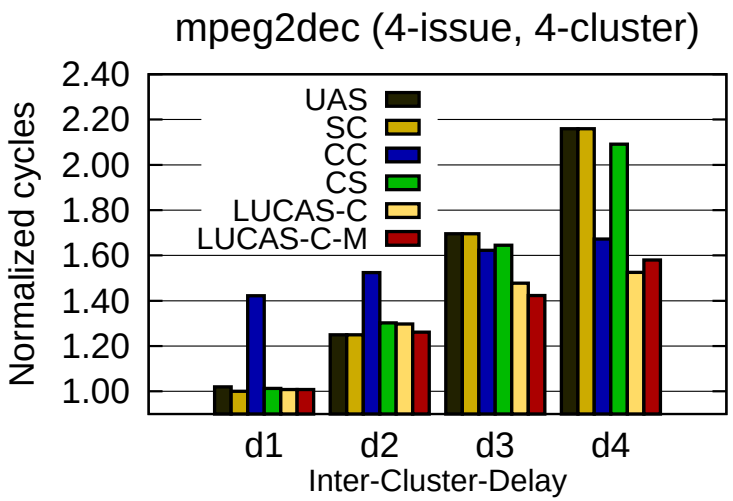
- Performance results, issue4
- Performance results, issue8
- Instruction distribution, issue4
- Instruction distribution, issue8
- Processor Configuration
- Congestion Threshold
- Mobility Threshold
- Definition of Mobility
- LUCAS Algorithm 1
- LUCAS Algorithm 2
- Bibliography

Performance Results (issue 4)









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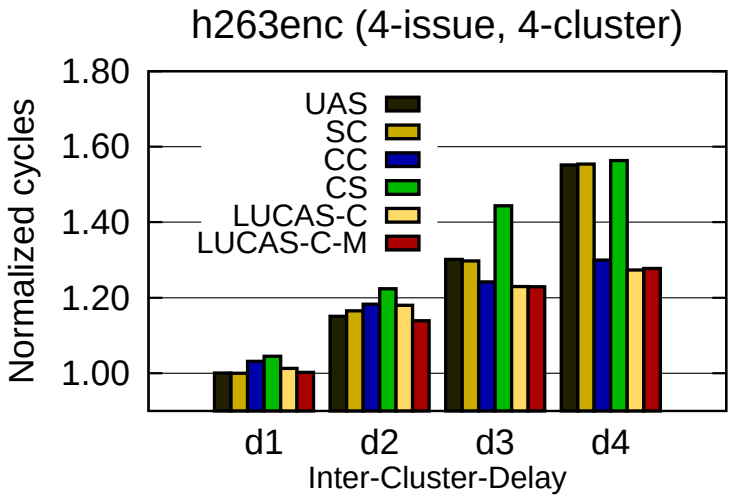

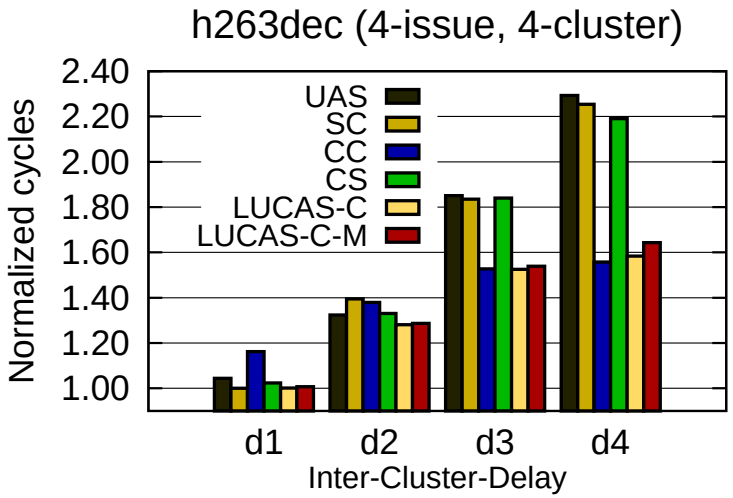

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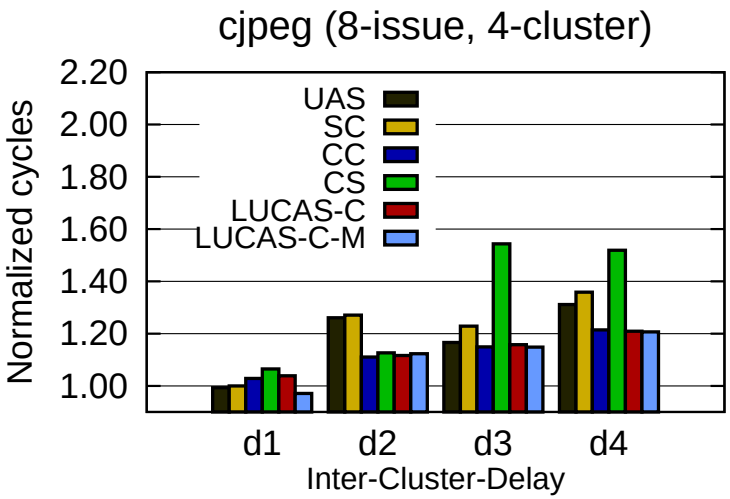

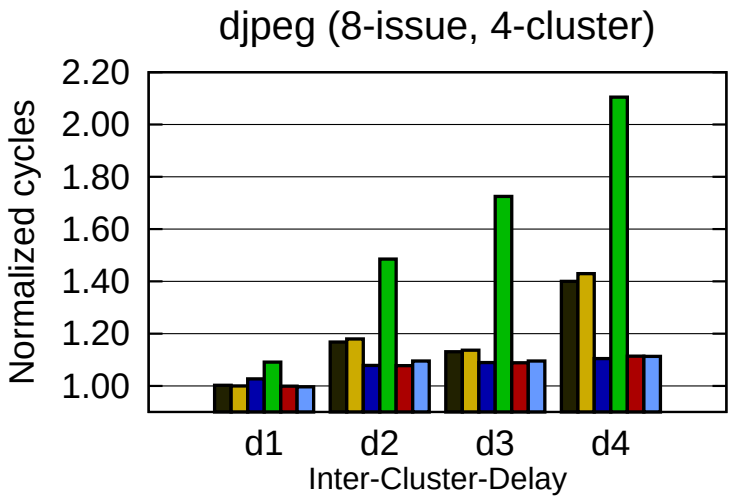

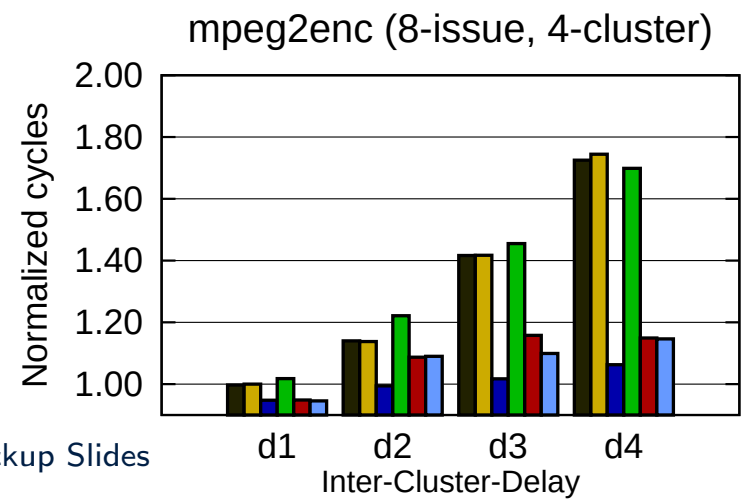

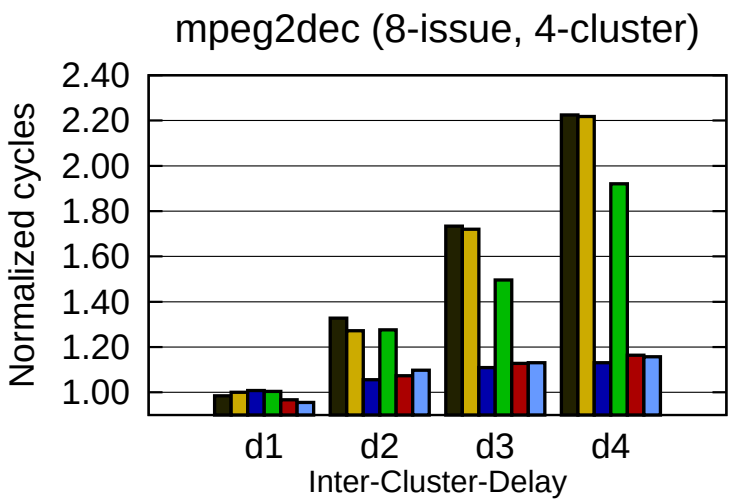

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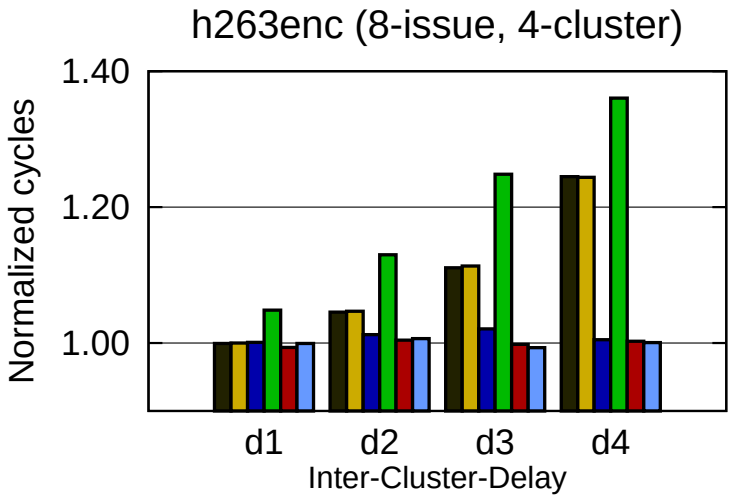

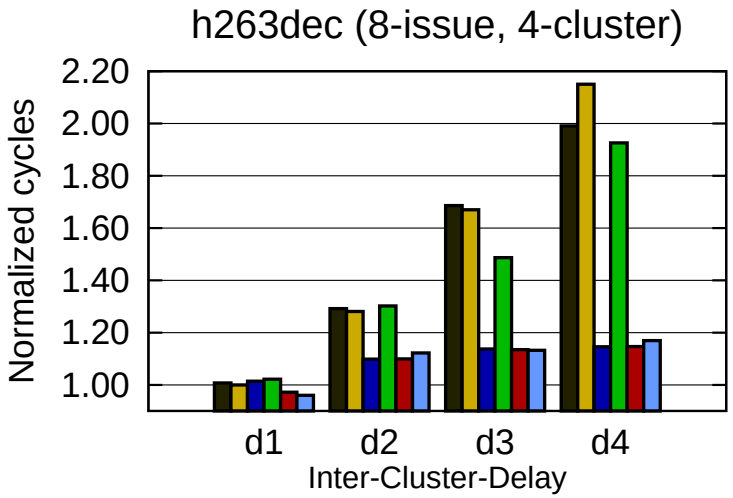

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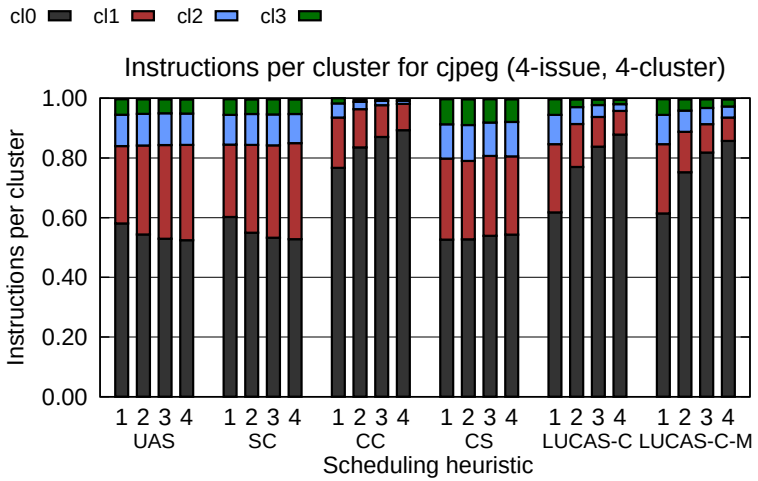

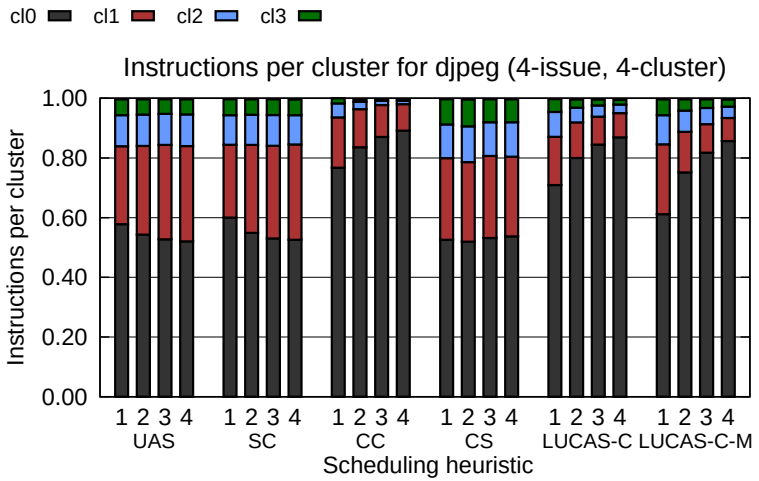

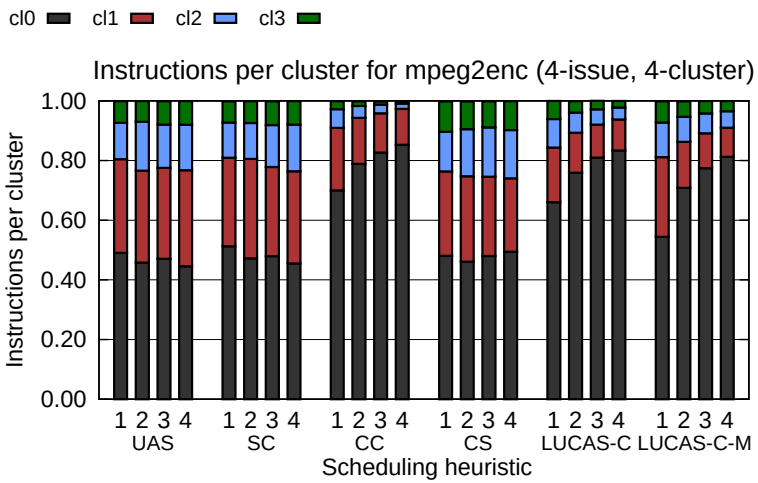

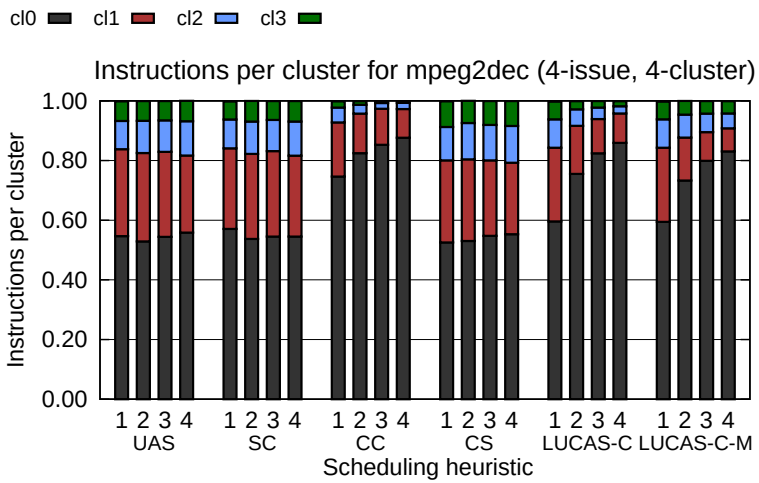

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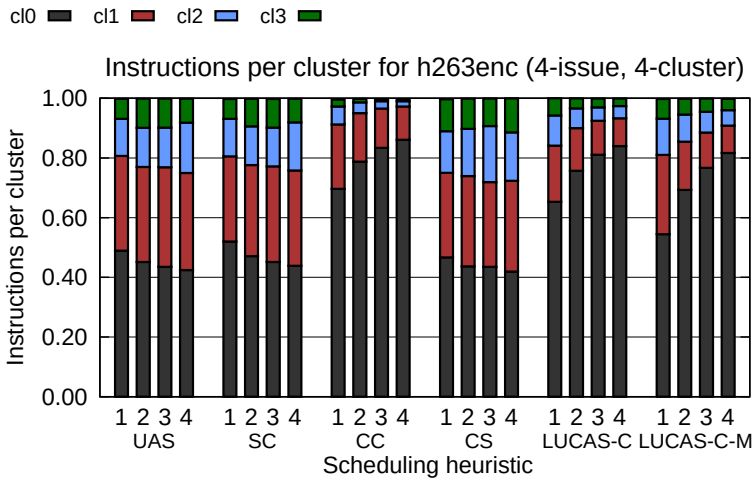

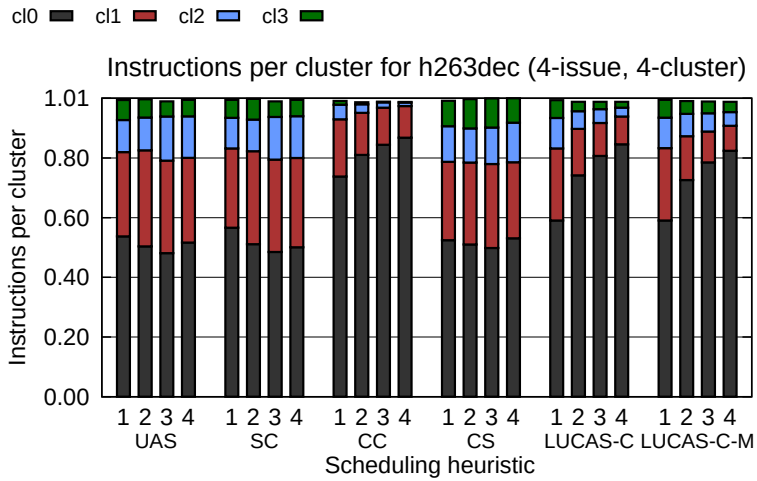

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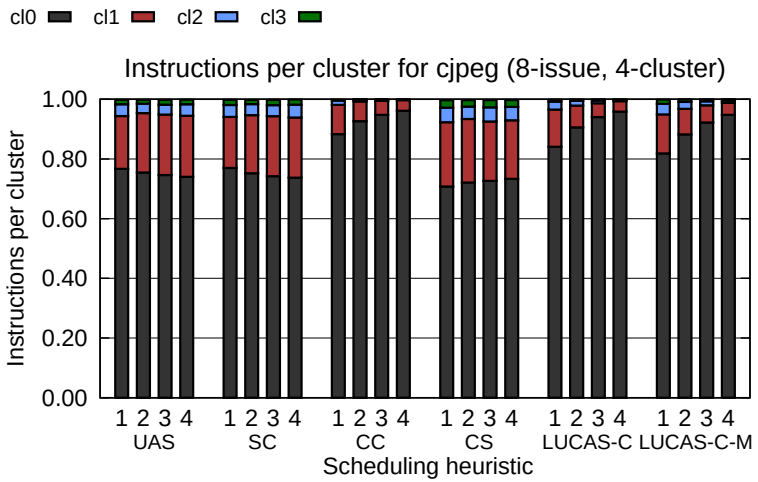

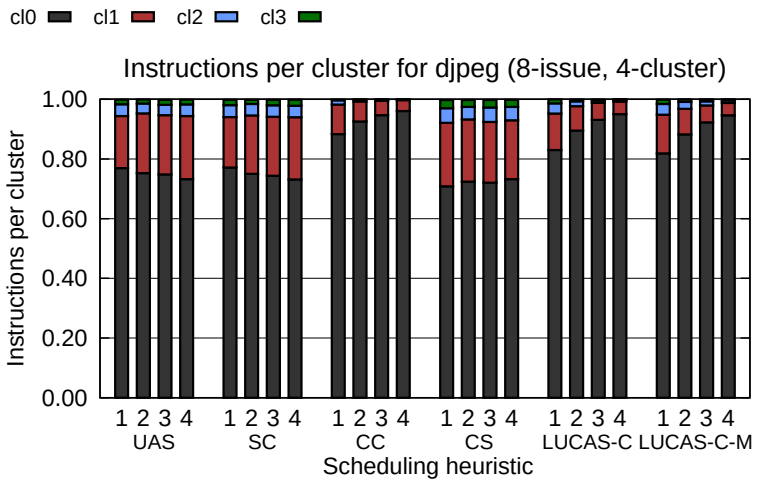

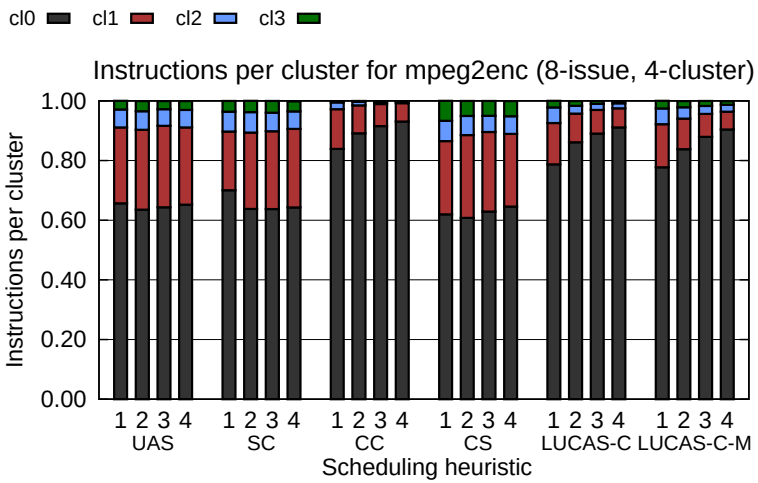

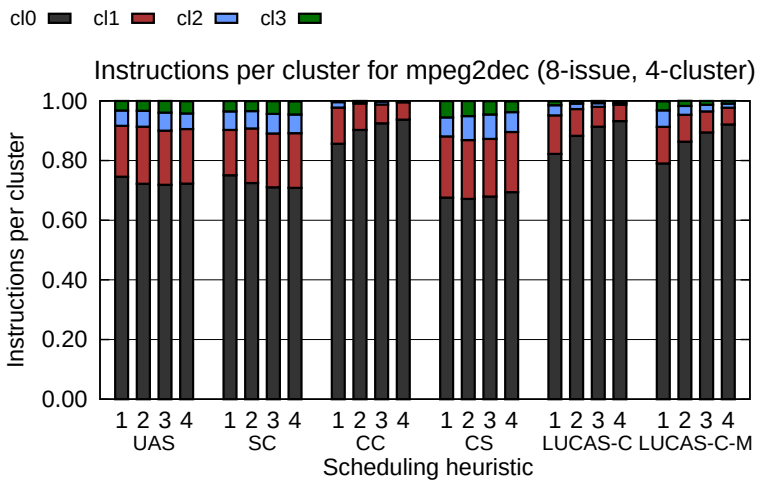

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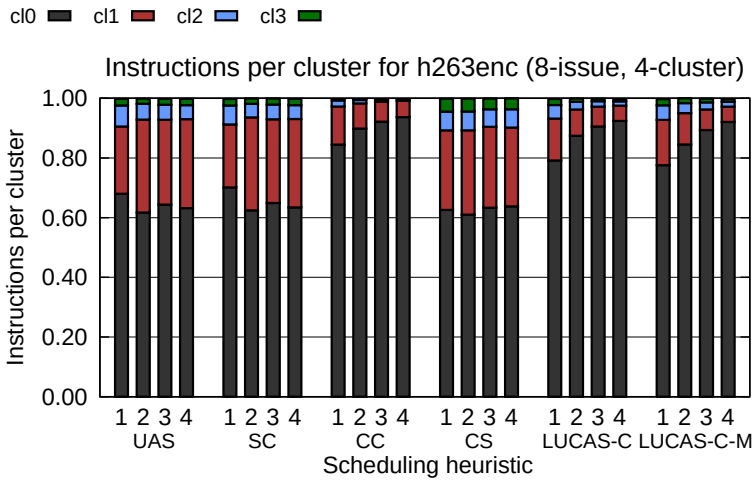
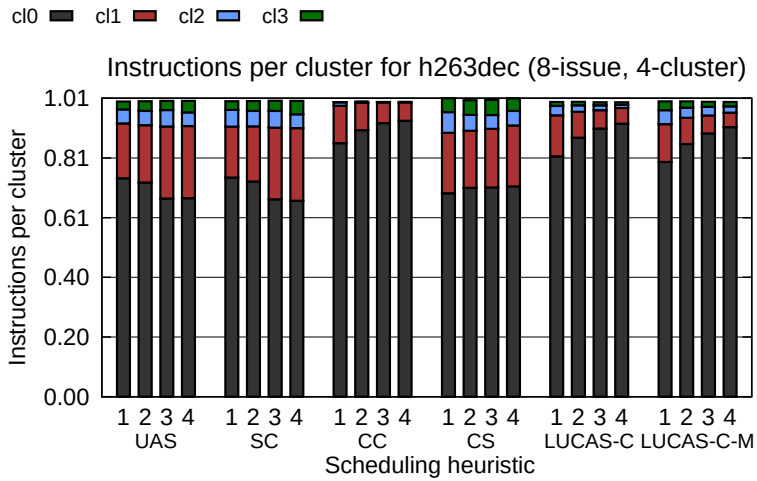




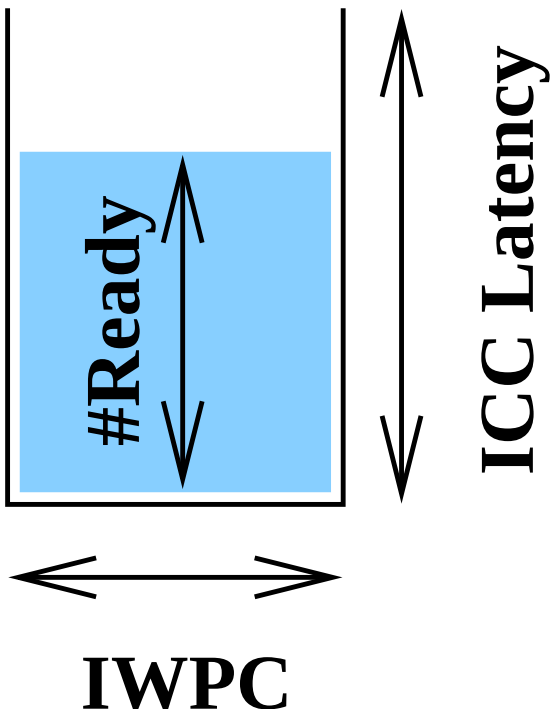
Backup Slides

Processor: IA64 based clustered VLIW				
Issue Width:	4 or 8			
Clusters:	4			
Instruction Latencies:	Same as Itanium2			
Register File:	(32GP, 32FL, 16PR) per cluster			
Inter-Cluster Delay:	1 - 4 cycles			
Inter-Cluster Bus Bandwidth:	∞			
Branch Prediction:	Perfect			
Cache: Levels 3 (same as Itanium2)				
Levels :	L1	L2	L3	Main Mem.
Size (Bytes):	16K	256K	3M	∞
Block size (Bytes):	64	128	128	-
Associativity:	4-Way	8-way	12-way	-
Latency (cycles):	1	5	12	150

Table: Processor configuration.

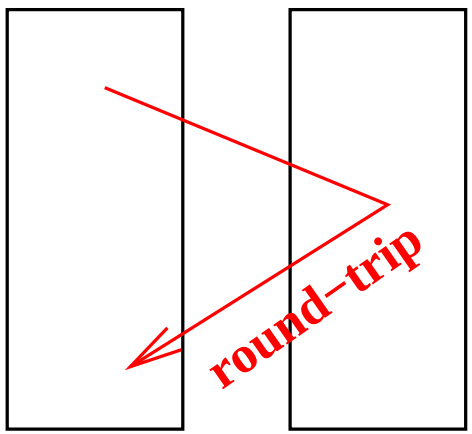
High Congestion Threshold

- High Congestion =
  Num. Ready instructions (cycle) $>$ CThr
- CThr = IWPC $\times$ ICC Latency



High Mobility Threshold

- High Mobility = (Mobility (insn) > MThr)
  MThr = IWPC × 2 × (ICC-Latency - 1)
- 2 × (ICC-Latency - 1) : is the round-trip latency



2 X (ICC−Latency − 1)

- IWPC × : Increases penalty as issue-width increases

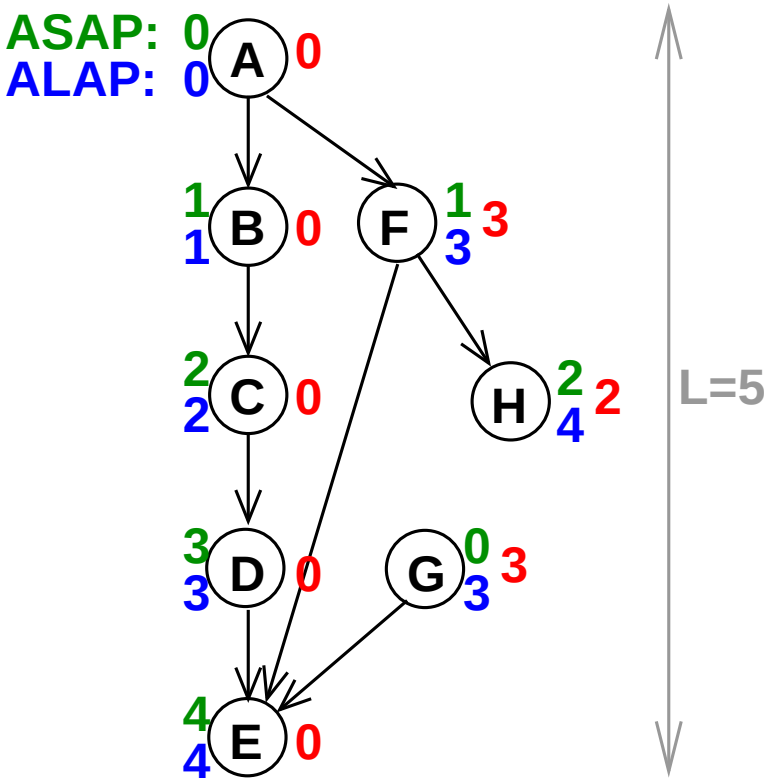
Algorithm

```
 1 /* LUCAS Scheduling and clustering. */
 2 lucas_schedule_and_cluster (DFG)
 3 {
 4  walk down the DFG and prioritize the nodes
 5  cycle = 0
 6  while (exist unscheduled nodes)
 7    Fill in ready_list
 8    sort ready_list based on priority
 9    for node in prioritized ready_list
10      best_cl = get_best_cluster(node.instr, cycle)
11      if (start_cycle (node.instr, cluster)<=cycle)
12        if (can issue node.instr on cycle)
13          if (can schedule Inter-Cluster Copies)
14            Emit ICCs and reg. rename node.instr
15            node.cluster = best_cl
16            Issue (node.instr, cycle, best_cl)
17            Update MOBILITY(node.instr) if it gets data from a
                  ↪distant cluster
18    cycle ++
19 }
```

```
 1 get_best_cluster (insn, cycle)
 2 {
 3  for cluster in all clusters
 4    heuristic[cluster] = lucas(insn,cluster)
 5  /* Find best cluster: MIN_CL */
 6  min_cl = 0
 7  for cli in clusters
 8    if (heuristic[cli] < heuristic[min_cl])
 9      min_cl = cli
10  return min_cl
11 }
12
13 /* Return the score of CLUSTER */
14 lucas (insn, cluster)
15 {
16  high_congestion = (#Ready-instr. > IWPC × ICD)
17  high_mobility = (MOBILITY(insn) > IWPC×2×(ICD-1))
18  if (high_congestion OR high_mobility)
19    return start_cycle (insn, cluster)
20  else
21    return completion_cycle (insn, cluster)
22 }
```

Instruction Mobility

MOBILITY = ALAP − ASAP



ASAP "as soon as possible"
the earliest scheduling cycle

ALAP "as late as possible"
the latest possible scheduling cycle
such that a valid schedule that
completes in L cycles is feasible

on a datapath with infinite resources.

Backup Slides

LUCAS vs UAS Complexity

Algorithm	Worst-case	Practical
UAS	$O(N^3)$	$O(N)$
LUCAS	$O(N^3)$	$O(N)$

LUCAS and UAS have a similar 3-nested loop structure and exhibit similar complexity. For all practical cases, the complexity is $O(N)$ and the worst-case is $O(N^3)$.

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