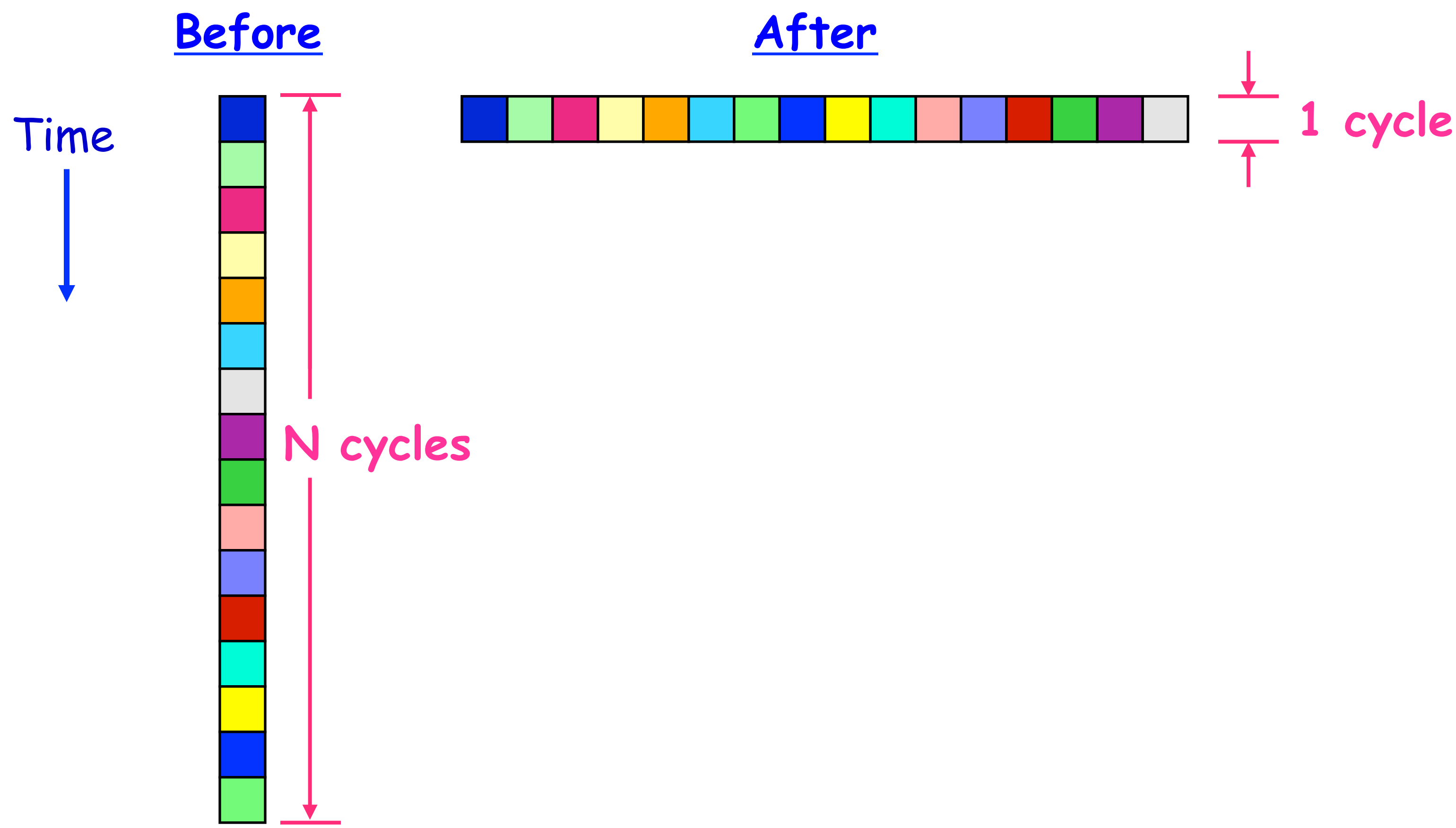
Lecture 18

List Scheduling & Global Scheduling

Reading: Chapter 10.3-10.4

Review: The Ideal Scheduling Outcome

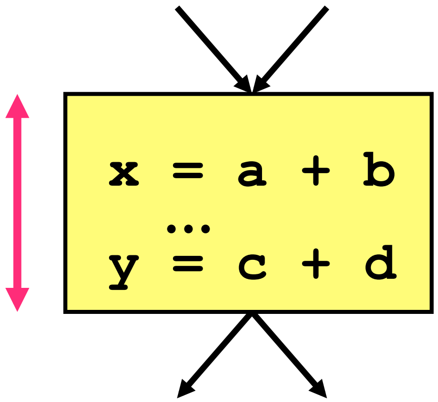
- What prevents us from achieving this ideal?



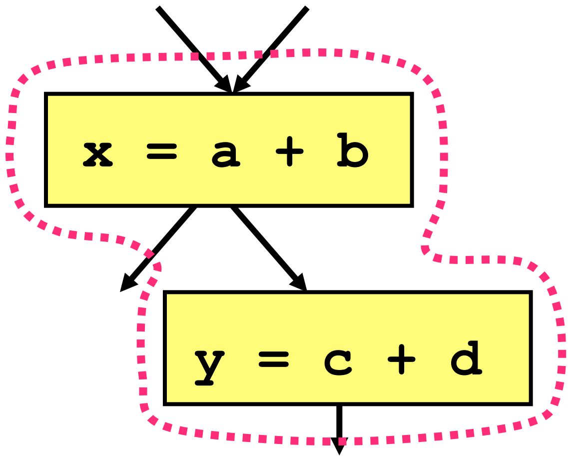
Review: Scheduling Constraints

- Hardware Resources
  - finite set of FUs with instruction type, bandwidth, and latency constraints
  - cache hierarchy also has many constraints
- Data Dependences
  - can't consume a result before it is produced
  - ambiguous dependences create many challenges
- Control Dependences
  - impractical to schedule for all possible paths
  - choosing an "expected" path may be difficult
    - recovery costs can be non-trivial if you are wrong

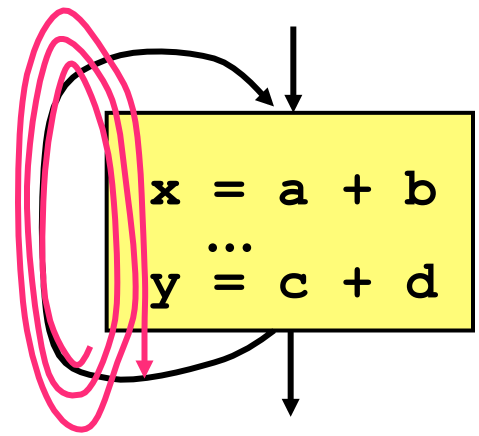
Scheduling Roadmap



List Scheduling:
- *within* a basic block



Global Scheduling:
- *across* basic blocks



Software Pipelining:
- *across* loop iterations

List Scheduling

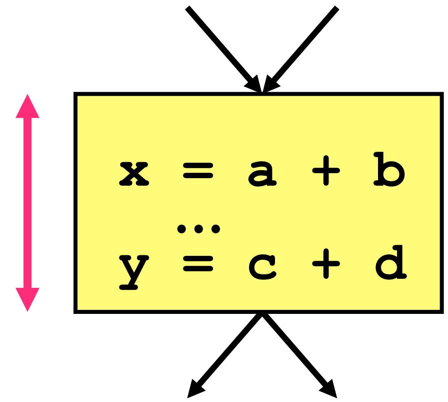
- The most common technique for scheduling instructions within a basic block

We don't need to worry about:

- control flow

We do need to worry about:

- data dependences
- hardware resources



- Even without control flow, the problem is still NP-hard

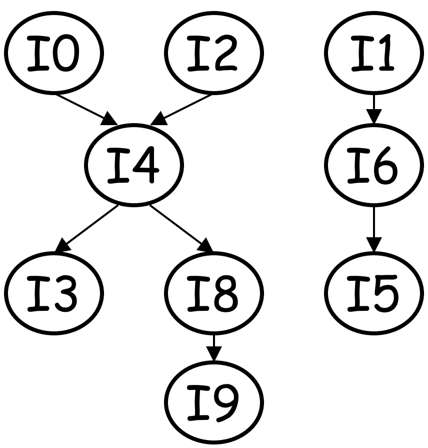
List Scheduling Algorithm: Inputs and Outputs

Algorithm reproduced from:

– "*An Experimental Evaluation of List Scheduling*", Keith D. Cooper, Philip J. Schielke, and Devika Subramanian. Rice University, Department of Computer Science Technical Report 98-326, September 1998.

Inputs:

Data Precedence Graph (DPG)



Machine Parameters

# of FUs:
2 INT, 1 FP

Latencies:
add = 1 cycle, …

Pipelining:
1 add/cycle, …

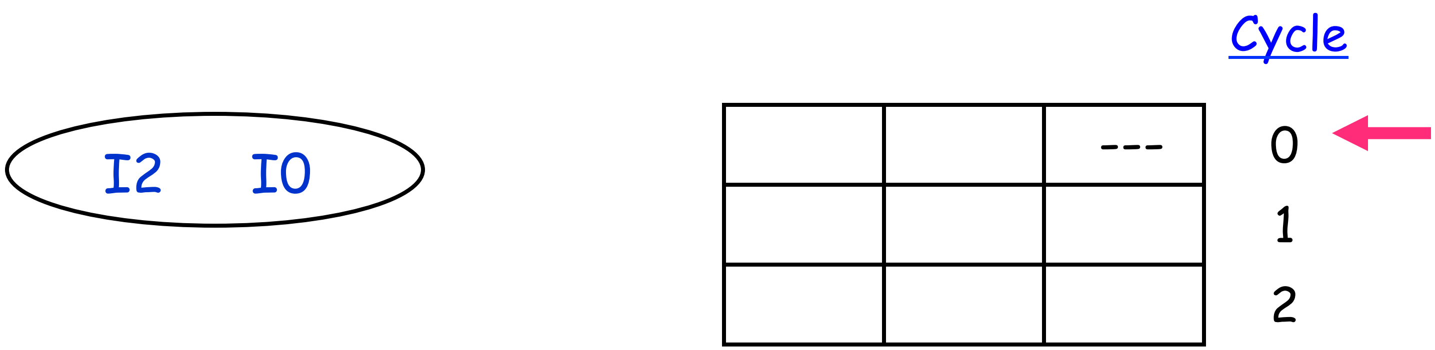
Output:

Scheduled Code

			Cycle
I0	I2	---	0
---	I1	I4	1
I3	I8	I6	2
I10	---	I11	3
I7	I9	I5	4

List Scheduling: The Basic Idea

- Maintain a list of instructions that are ready to execute
  - data dependence constraints would be preserved
  - machine resources are available
- Moving cycle-by-cycle through the schedule template:
  - choose instructions from the list & schedule them
  - update the list for the next cycle



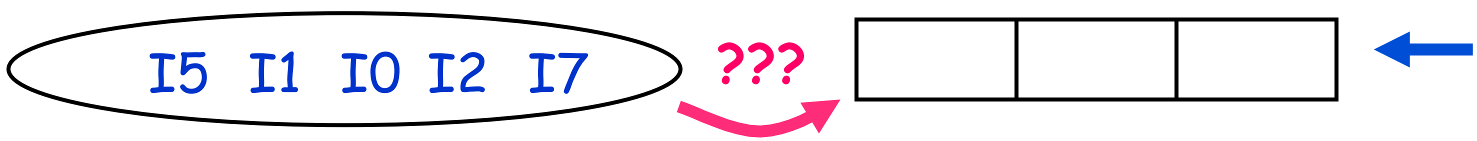
What Makes Life Interesting: Choice

Easy case:

– all ready instructions can be scheduled this cycle

Interesting case:

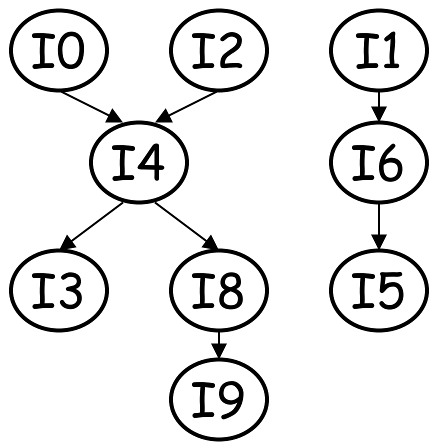
– we need to pick a subset of the ready instructions



- List scheduling makes choices based upon *priorities*
  – *assigning priorities correctly is a key challenge*

Intuition Behind Priorities

- Intuitively, what should the priority correspond to?
- What factors are used to compute it?
  - data dependences?
  - machine parameters?



<u>\# of FUs:</u>
2 INT, 1 FP
<u>Latencies:</u>
add = 1 cycle, …
<u>Pipelining:</u>
1 add/cycle, …

Representing Data Dependences: The Data Precedence Graph (DPG)

- Two different kinds of edges:

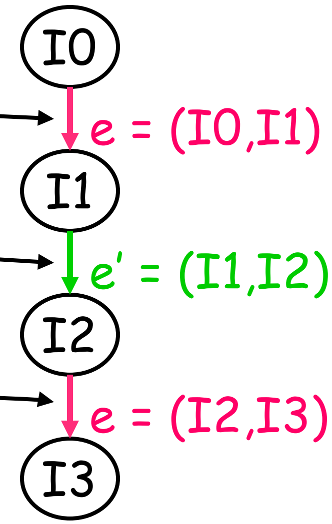
Code

```
I0: x = 1;
I1: y = x;
I2: x = 2;
I3: z = x;
```

true "edges": **E**
(read-after-write)

"anti-edges": **E'**
(write-after-read)

DPG

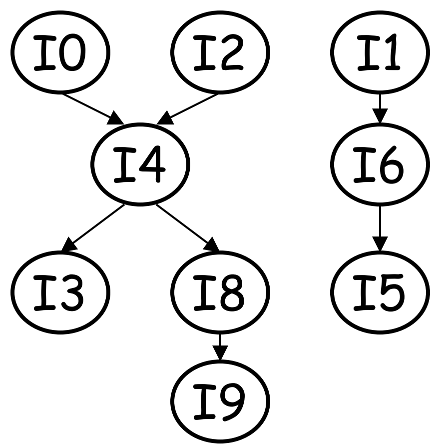


- Why distinguish them?
  - do they affect scheduling differently?
- What about output dependences?

Computing Priorities

- Let's start with just true dependences (i.e. "edges" in DPG)
- Priority = *latency-weighted depth* in the DPG

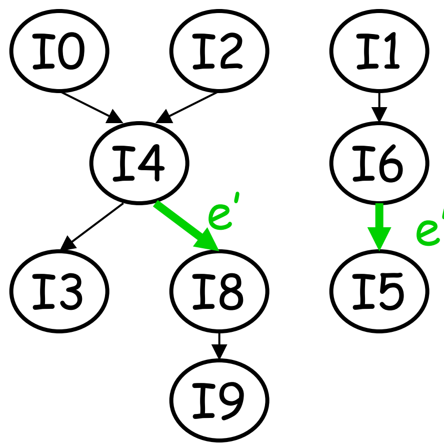
$$priority(x) = max(\forall_{l \in leaves(DPG)} \forall_{p \in paths(x,\ldots,l)} \sum_{p_i = x}^{l} latency(p_i))$$



Computing Priorities (Cont.)

- Now let's also take anti-dependences into account
  - i.e. anti-edges in the set E'

$$priority(x) = \begin{cases} latency(x) & \text{if } x \text{ is a leaf} \\ max(latency(x) + max_{(x,y)\in E}(priority(y)), \\ \quad max_{(x,y)\in E'}(priority(y))) & otherwise. \end{cases}$$



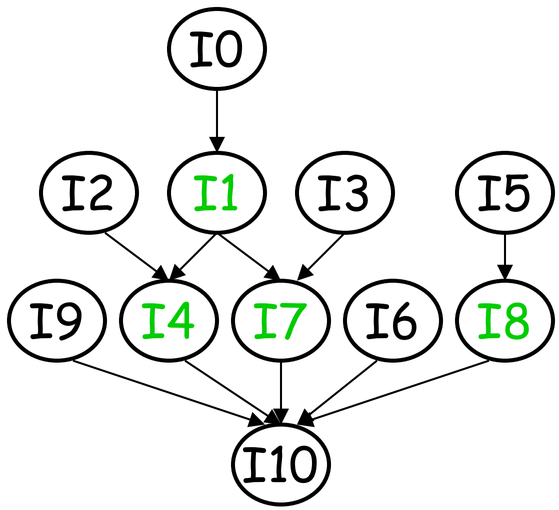
List Scheduling Algorithm

```
cycle = 0;
ready-list = root nodes in DPG; inflight-list = {};

while ((|ready-list|+|inflight-list| > 0) && an issue slot is available) {
    for op = (all nodes in ready-list in descending priority order) {
        if (an FU exists for op to start at cycle) {
            remove op from ready-list and add to inflight-list;
            add op to schedule at time cycle;
            if (op has an outgoing anti-edge)
                add all targets of op's anti-edges that are ready to ready-list;
        }
    }
    cycle = cycle + 1;
    for op = (all nodes in inflight-list)
        if (op finishes at time cycle) {
            remove op from inflight-list;
            check nodes waiting for op & add to ready-list if all operands
    available;
        }
    }
}
```

Example

```
I0:  a = 1
I1:  f = a + x
I2:  b = 7
I3:  c = 9
I4:  g = f + b
I5:  d = 13
I6:  e = 19;
I7:  h = f + c
I8:  j = d + y
I9:  z = -1
I10: JMP L1
```



		Cycle
		0
		1
		2
		3
		4
		5
		6

- 2 identical fully-pipelined FUs
- adds take 2 cycles; all other insts take 1 cycle

Example

```
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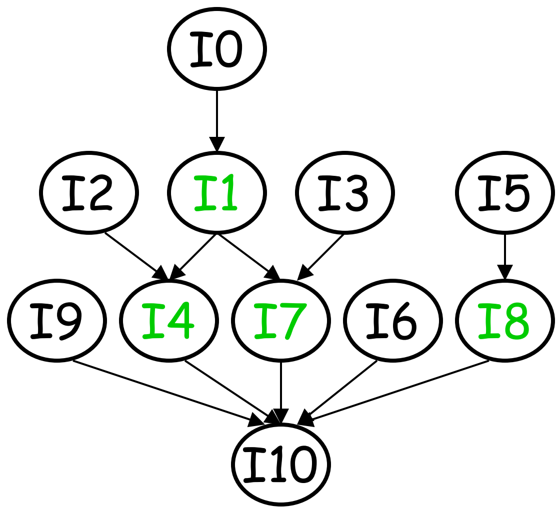

		Cycle
I0	I2	0
I1	I3	1
I5	I9	2
I4	I7	3
I8	I6	4
---	---	5
I10		6

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What if We Break Ties Differently?

```
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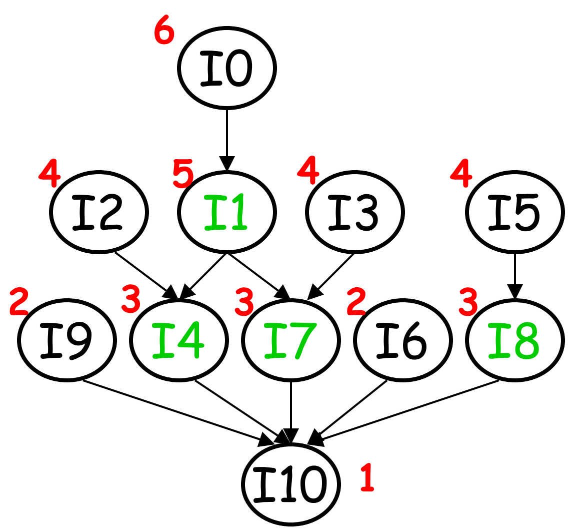

		Cycle
		0
		1
		2
		3
		4
		5
		6

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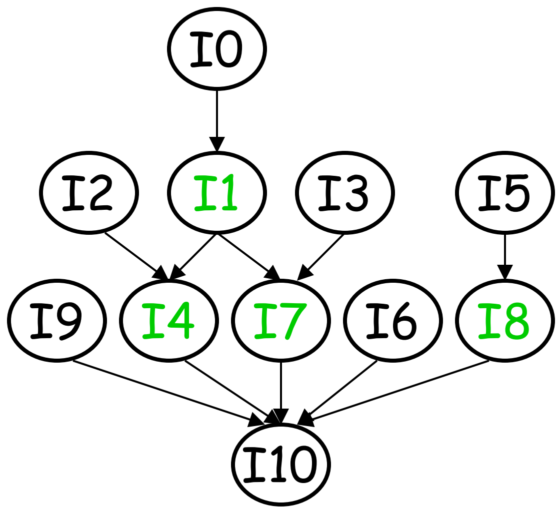
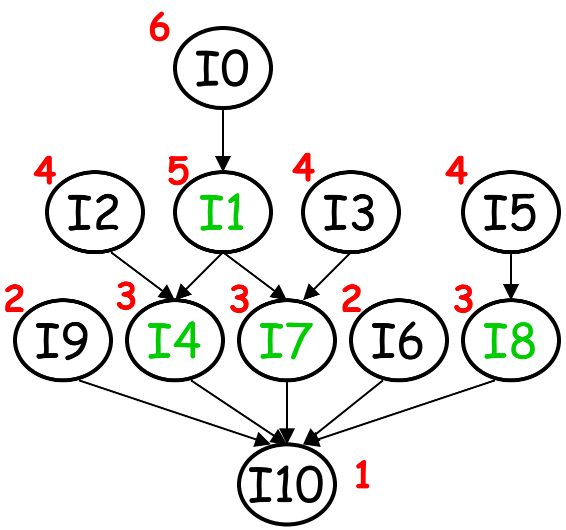


		Cycle
I0	I2	0
I1	I5	1
I3	I8	2
I4	I7	3
I9	I6	4
I10		5
		6

- 2 identical fully-pipelined FUs
- adds take 2 cycles; all other insts take 1 cycle

Contrasting the Two Schedules

- Breaking ties arbitrarily may not be the best approach



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		Cycle
I0	I2	0
I1	I5	1
I3	I8	2
I4	I7	3
I9	I6	4
I10		5

Backward List Scheduling

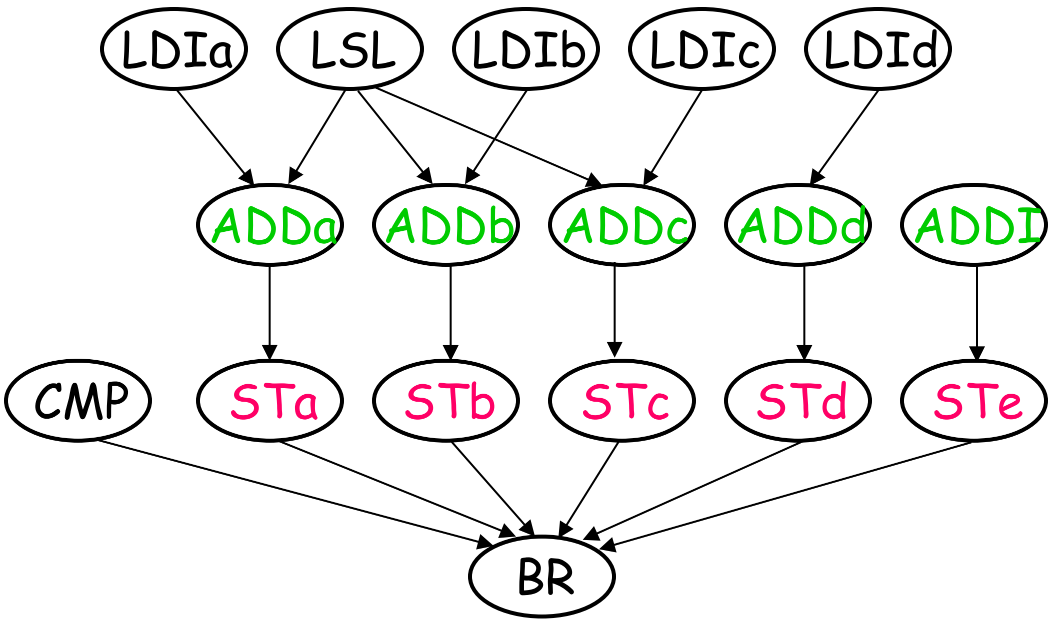
Modify the algorithm as follows:

- reverse the direction of all edges in the DPG
- schedule the *finish times* of each operation
  - start times must still be used to ensure FU availability

Impact of scheduling backwards:

- clusters operations near the end (vs. the beginning)
- may be either better or worse than forward scheduling

Backward List Scheduling Example: Let's Schedule it Forward First

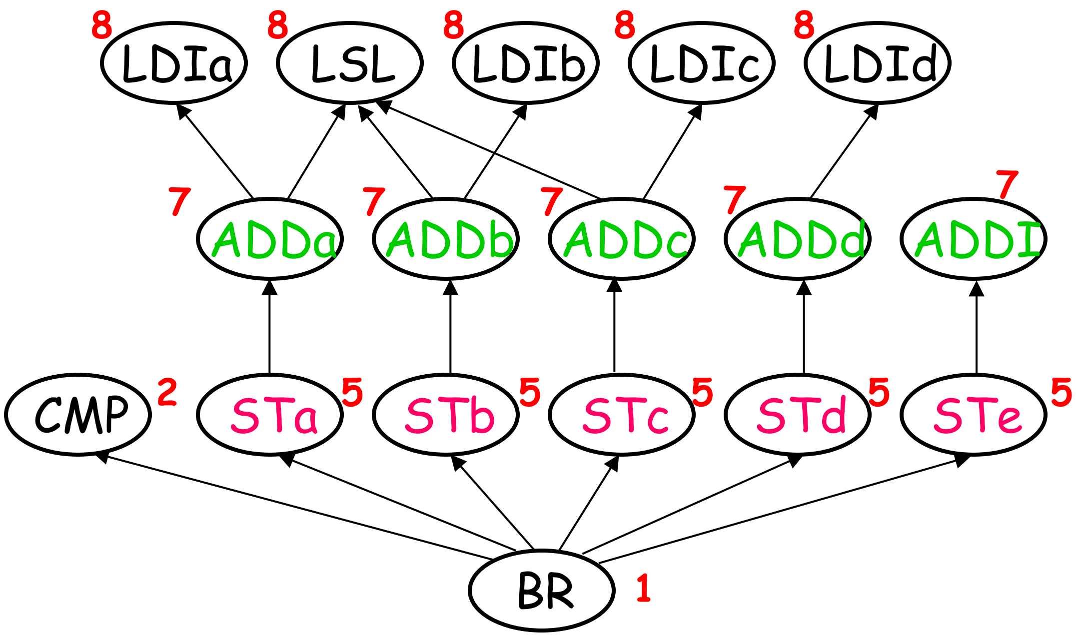


INT	INT	MEM	Cycle
LDIa	LSL	----	0
LDIb	LDIc	----	1
LDId	ADDa	----	2
ADDb	ADDc	----	3
ADDd	ADDI	STa	4
CMP	----	STb	5
----	----	STc	6
----	----	STd	7
----	----	STe	8
----	----	----	9
----	----	----	10
----	----	----	11
BR	----	----	12

Hardware parameters:

- 2 INT units: ADDs take 2 cycles; others take 1 cycle
- 1 MEM unit: stores (ST) take 4 cycles

Now Let's Try Scheduling Backward



INT	INT	MEM	Cycle
LDIa	----	----	0
ADDI	LSL	----	1
ADDd	LDIc	----	2
ADDc	LDId	STe	3
ADDb	LDIa	STd	4
ADDa	----	STc	5
----	----	STb	6
----	----	STa	7
----	----	----	8
----	----	----	9
CMP	----	----	10
BR	----	----	11

Hardware parameters:

- 2 INT units: ADDs take 2 cycles; others take 1 cycle
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Contrasting Forward vs. Backward List Scheduling

Forward

INT	INT	MEM	Cycle
LDIa	LSL	----	0
LDIb	LDIc	----	1
LDId	ADDa	----	2
ADDb	ADDc	----	3
ADDd	ADDI	STa	4
CMP	----	STb	5
----	----	STc	6
----	----	STd	7
----	----	STe	8
----	----	----	9
----	----	----	10
----	----	----	11
BR	----	----	**12**

Backward

INT	INT	MEM	Cycle
LDIa	----	----	0
ADDI	LSL	----	1
ADDd	LDIc	----	2
ADDc	LDId	STe	3
ADDb	LDIa	STd	4
ADDa	----	STc	5
----	----	STb	6
----	----	STa	7
----	----	----	8
----	----	----	9
CMP	----	----	10
BR	----	----	**11**

- backward scheduling clusters work near the end
- backward is better in this case, but this is not always true

Evaluation of List Scheduling

Cooper *et al.* propose "RBF" scheduling:

- schedule each block M times forward & backward
- break any priority ties randomly

For real programs:

- regular list scheduling works very well

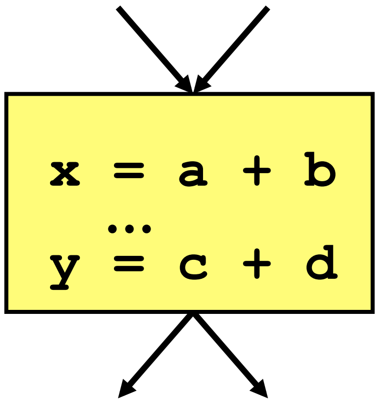
For synthetic blocks:

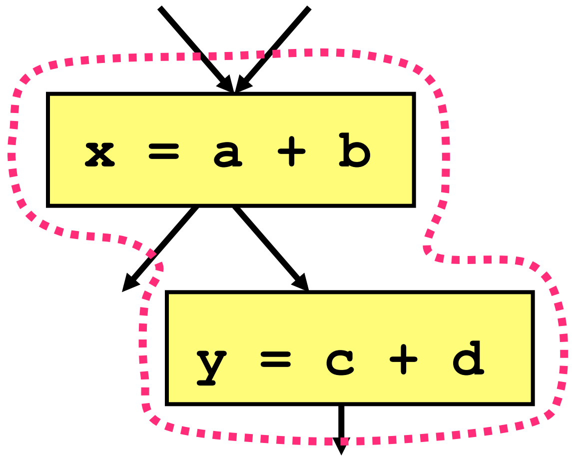
- RBF wins when "available parallelism" (AP) is ~2.5
- for smaller AP, scheduling is too constrained
- for larger AP, any decision tends to work well

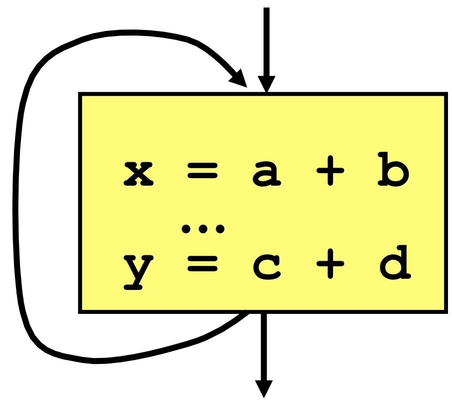
List Scheduling Wrap-Up

- The priority function can be arbitrarily sophisticated
  - e.g., filling branch delay slots in early RISC processors
- List scheduling is widely used, and it works fairly well
- It is limited, however, by basic block boundaries

Scheduling Roadmap







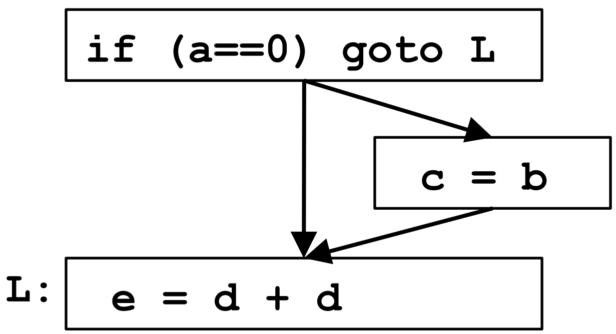
List Scheduling:
- within a basic block

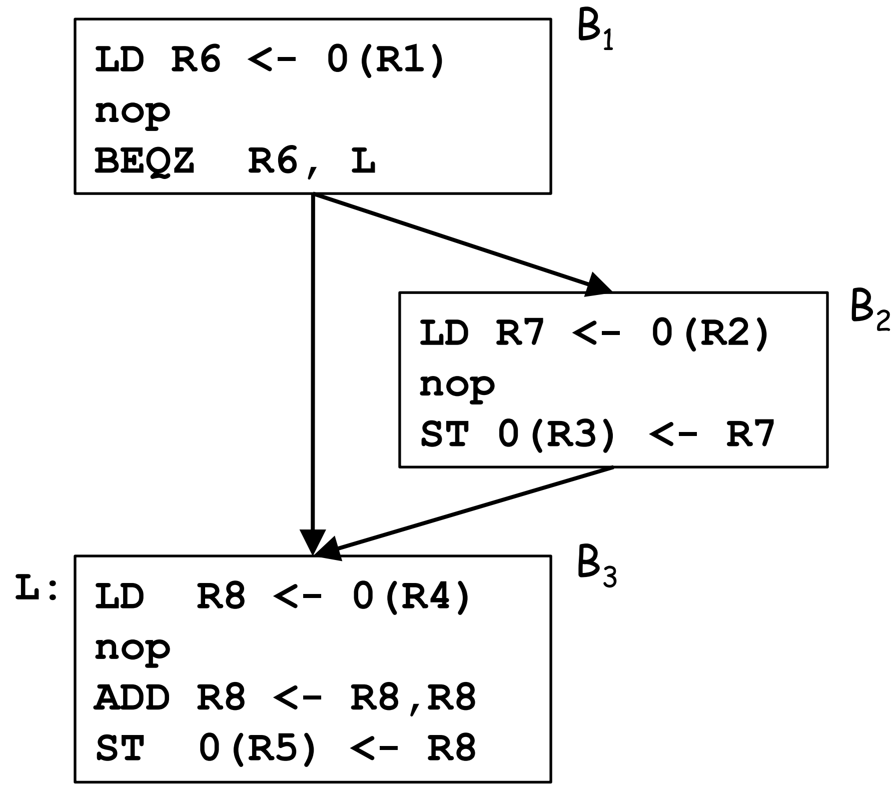
Global Scheduling:
- *across* basic blocks

Software Pipelining:
- *across* loop iterations

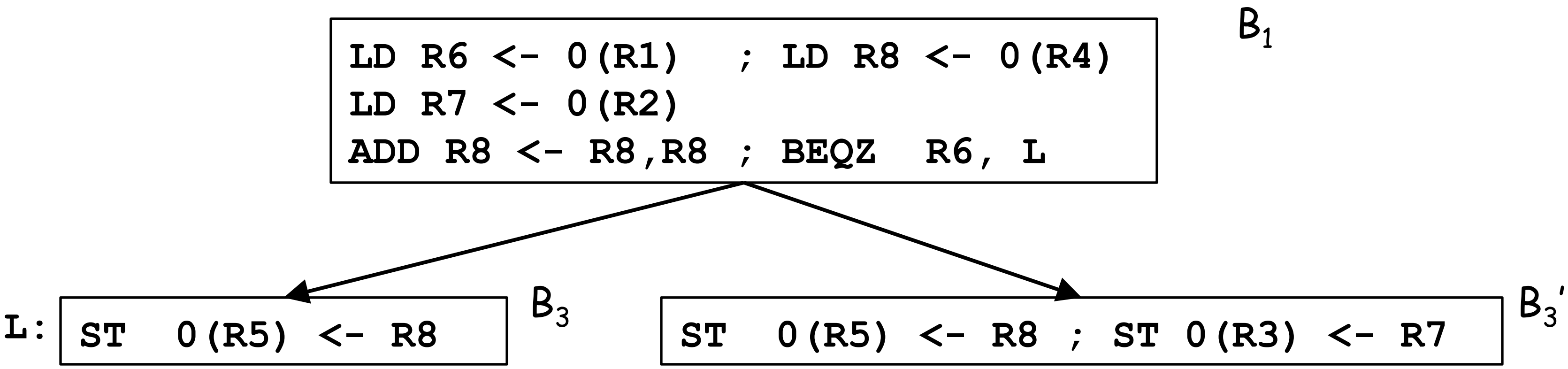
Introduction to Global Scheduling

Assume each clock can execute 2 operations of any kind.

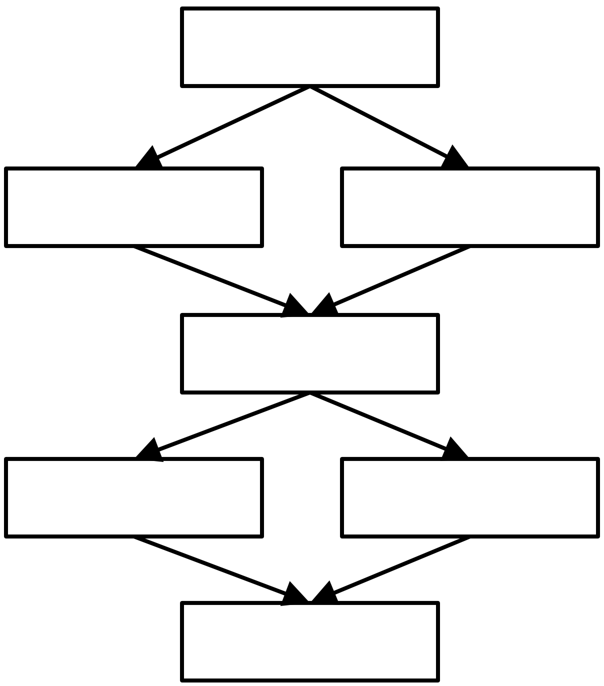




Result of Code Scheduling



Terminology



Control equivalence:

- Two operations o_1 and o_2 are *control equivalent* if o_1 is executed if and only if o_2 is executed.

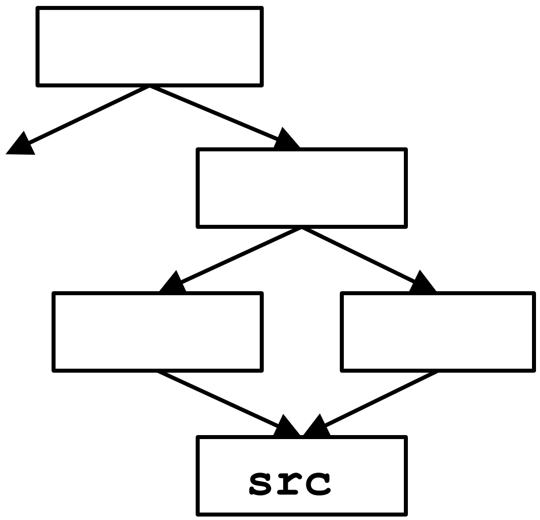
Control dependence:

- An op o_2 is *control dependent* on op o_1 if the execution of o_2 depends on the outcome of o_1.

Speculation:

- An operation o is *speculatively* executed if it is executed before all the operations it depends on (control-wise) have been executed.
- Requirements:
  - does not raise an exception
  - satisfies data dependences

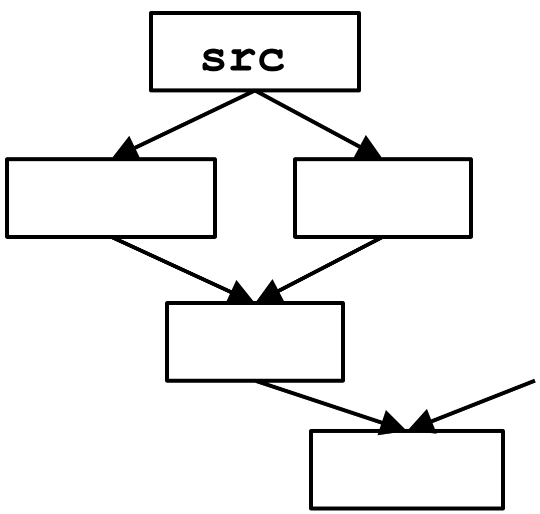
Code Motions



Goal: Shorten execution time probabilistically

Moving instructions up:

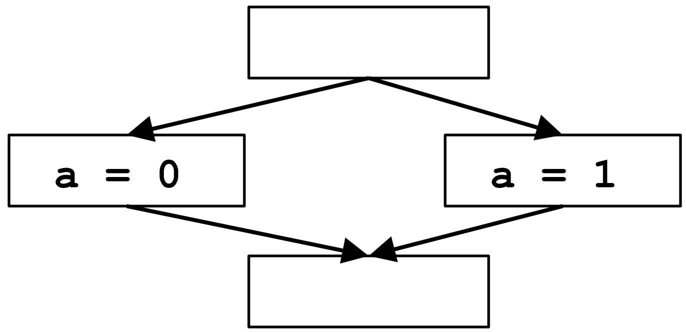
- Move instruction to a cut set (from entry)
- Speculation: even when not anticipated.



Moving instructions down:

- Move instruction to a cut set (from exit)
- May execute extra instruction
- Can duplicate code

A Note on Data Dependences



General-Purpose Applications

- **Lots of data dependences**
- **Key performance factor: memory latencies**
- **Move memory fetches up**
  - Speculative memory fetches can be expensive
- **Control-intensive: get execution profile**
  - Static estimation
    - Innermost loops are frequently executed
      - back edges are likely to be taken
    - Edges that branch to exit and exception routines are not likely to be taken
  - Dynamic profiling
    - Instrument code and measure using representative data

A Basic Global Scheduling Algorithm

- **Schedule innermost loops first**
- **Only upward code motion**
- **No creation of copies**
- **Only one level of speculation**

Program Representation

- **A region in a control flow graph is:**
  - a set of basic blocks and all the edges connecting these blocks,
  - such that control from outside the region must enter through a single entry block.
- **A procedure is represented as a hierarchy of regions**
  - The whole control flow graph is a region
  - Each natural loop in the flow graph is a region
  - Natural loops are hierarchically nested
- **Schedule regions from inner to outer**
  - treat inner loop as a black box unit
    - can schedule around it but not into it
  - ignore all the loop back edges → get an acyclic graph

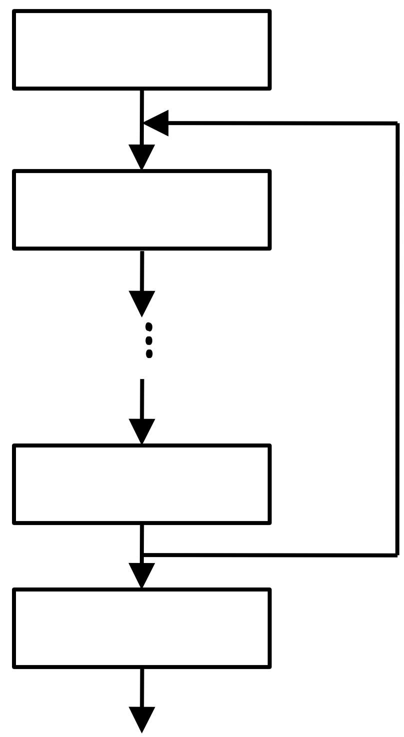
Algorithm

```
Compute data dependences;
For each region from inner to outer {
    For each basic block B in prioritized topological order {
        CandBlocks = ControlEquiv{B} ∪
                     Dominated-Successors{ControlEquiv{B}};
        CandInsts = ready operations in CandBlocks;
        For (t = 0, 1, ... until all operations from B are scheduled)  {
            For (n in CandInst in priority order) {
                if (n has no resource conflicts at time t) {
                    S(n) = < B, t >
                    Update resource commitments
                    Update data dependences
                }
            }
            Update CandInsts;
        }}}
```

Priority functions: non-speculative before speculative

Extensions

- Prepass before scheduling: loop unrolling
- Especially important to move operation up loop back edges



Summary

- **Global scheduling**
  - Legal code motions
  - Heuristics