# Lecture 7

# Instruction Scheduling

I Basic Block Scheduling

II Global Scheduling (for Non-Numeric Code)

Reading: Chapter 10.3 - 10.4

# I. Scheduling Constraints

- **Data dependences**
  - The operations must generate the same results as the corresponding ones in the original program.
- **Control dependences**
  - All the operations executed in the original program must be executed in the optimized program
- **Resource constraints**
  - No over-subscription of resources.

# Data Dependence

- **Must maintain order of accesses to potentially same locations**
  - True dependence: write -> read (RAW hazard)

    a = . . .
    = a

  - Output dependence: write -> write (WAW hazard)

    a = . . .
    a = . . .

  - Anti-dependence: read -> write (WAR hazard)

    = a
    a =

- **Data Dependence Graph**
  - Nodes: operations
  - Edges: $n_1$ -> $n_2$ if $n_2$ is data dependent on $n_1$
    labeled by the execution length of $n_1$

# Analysis on Memory Variables

- **Undecidable in general**

```
read x
read y
A[x] = ...
...   = A[y]
```

- **Two memory accesses can potentially be the same unless proven otherwise**

- **Classes of analysis**
  - simple: base+offset1 = base+offset2?
  - "data dependence analysis":
    Array accesses whose indices are affine expressions of loop indices
    A[2i] = A[2i+1]?
  - interprocedural analysis: global = parameter?
  - pointer analysis: pointer1 = pointer2?

- **Data dependence analysis is useful for many other purposes**

# Resource Constraints

- **Each instruction type has a resource reservation table**

Functional units

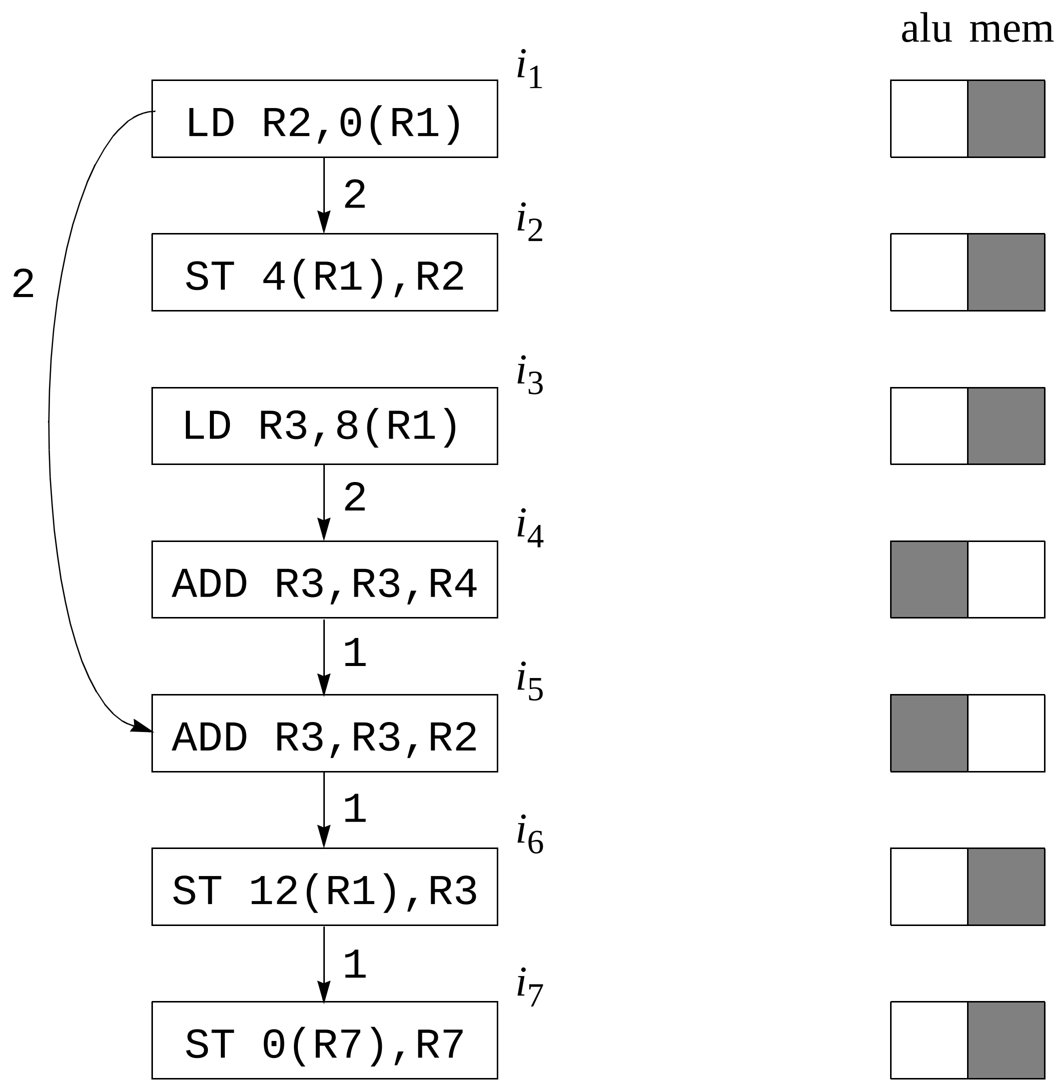
| Time | ld | st | alu | fmpy | fadd | br | ··· |
|---|---|---|---|---|---|---|---|
| 0 | | | | | | | |
| 1 | | | | | | | |
| 2 | | | | | | | |

  - Pipelined functional units: occupy only one slot
  - Non-pipelined functional units: multiple time slots
  - Instructions may use more than one resource
  - Multiple units of same resource
  - Limited instruction issue slots
    may also be managed like a resource

# Example of a Machine Model

- Each instruction can execute 2 operations
- 1 ALU operation or branch operation
  `Op dst,src1,src2` executes in 1 clock
- 1 load or store operation
  `LD dst, addr` result is available in 2 clocks
  pipelined: can issue `LD` next clock
  `ST src, addr` executes in 1 clock cycle

# Basic Block Scheduling



# With Resource Constraints

- **NP-complete in general => Heuristics time!**
- **List Scheduling**

READY = nodes with 0 predecessors

Loop until READY is empty {

Let **n** be the node in READY with **highest priority**

Schedule **n** in the earliest slot
that satisfies precedence + resource constraints

Update predecessor count of **n**’s successor nodes
Update READY

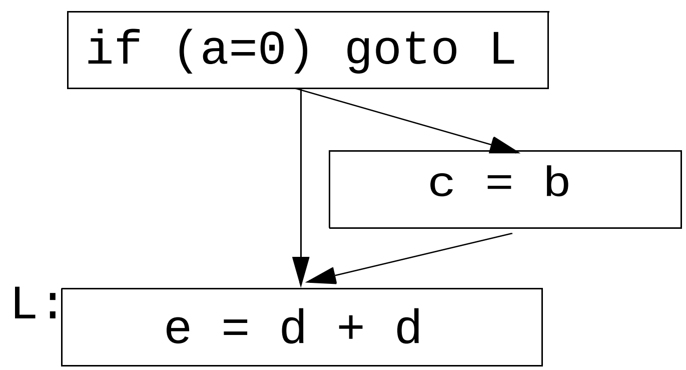
}

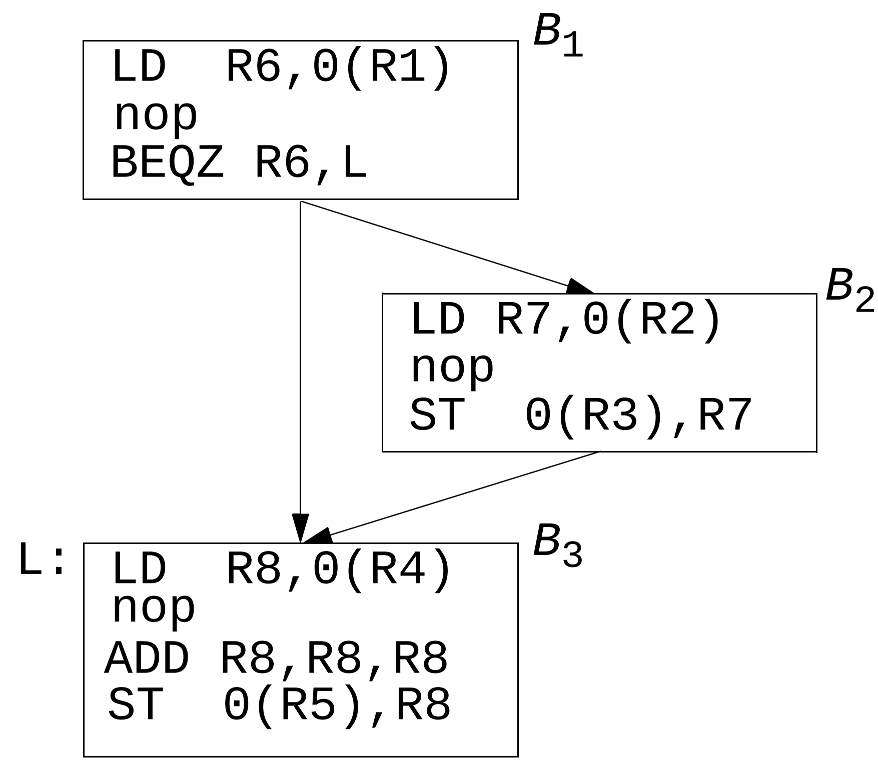
# List Scheduling

- **Scope: DAGs**
  - Schedules operations in topological order
  - Never backtracks

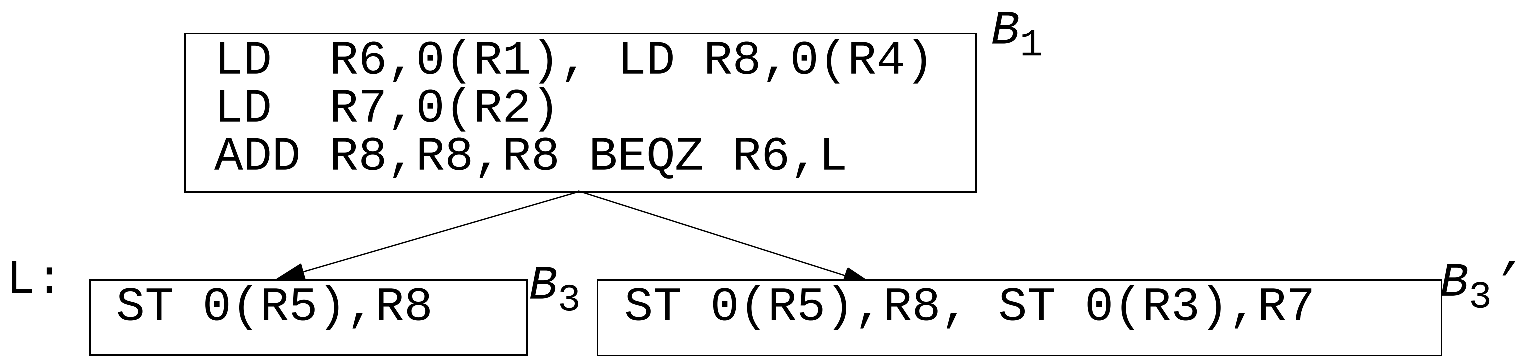
- **Variations**
  - Priority function for node **n**
    - critical path: max clocks from **n** to any node
    - resource requirements
    - source order

# II. Introduction to Global Scheduling

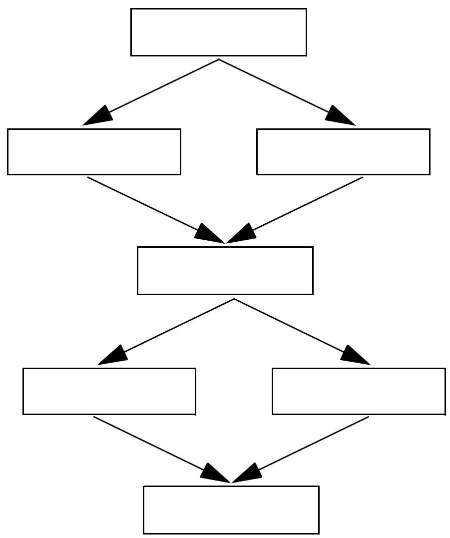


# Result of Code Scheduling



# 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.

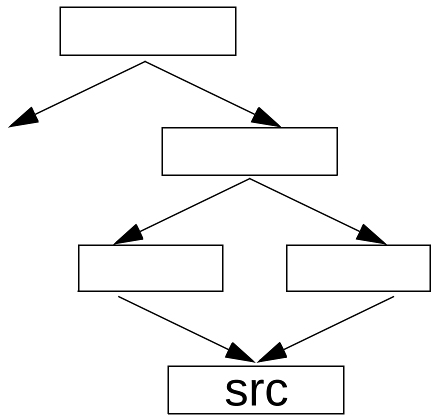
Control dependence

- 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.
- Requirement: Raises no exception, satisfies data dependences

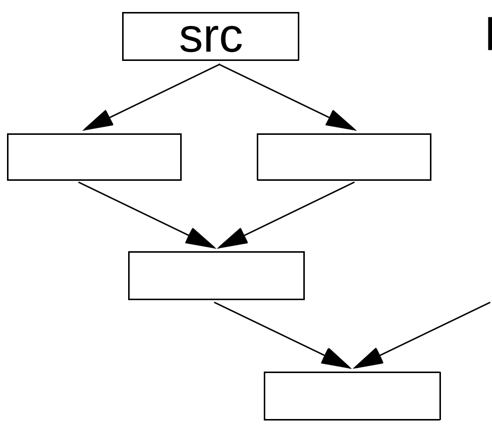
# Code Motions




Goal: Shorten execution time probabilistically

Moving instructions up

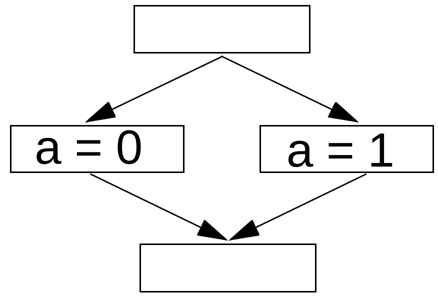
- Move instruction to a cut set (from entry)
- Speculation: even when not anticipated.




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 function 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

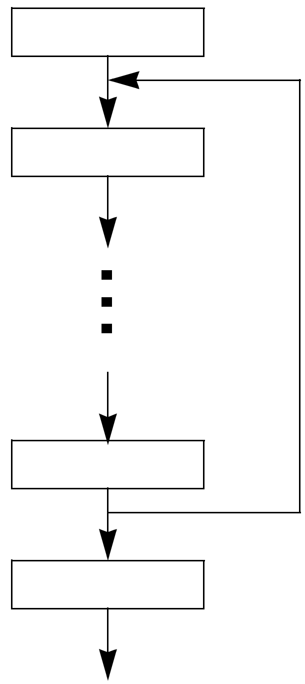
# Algorithm

```
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

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