Lecture 7

Introduction to Instruction Scheduling

I. Basic Block Scheduling
II. Global Scheduling Concepts

Reading: Chapter 10.3 – 10.4

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.

Same constraints for instruction level / processor level parallelism

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 = ...
```

Quiz: What is missing?

- **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
  - A resource type may have multiple units
  - Limited instruction issue slots
    - may also be managed like a resource

Example of a Machine Model

- Each machine cycle can execute 2 operations
- 1 ALU operation or branch operation

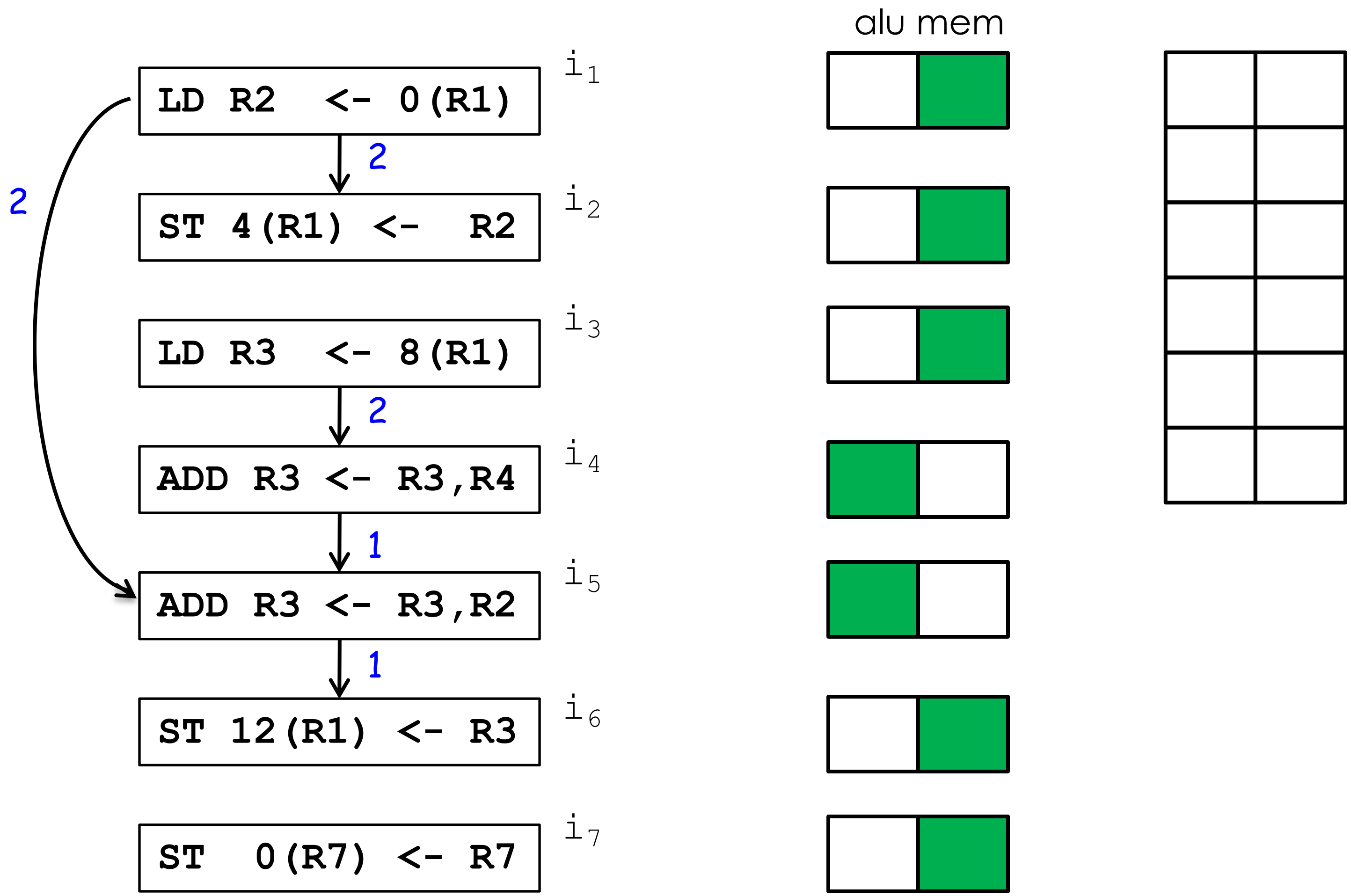
  `Op dst,src1,src2` executes in 1 clock

- 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
  - can issue LD/ST to any location in the next clock
  - a write buffer is often used to hold the result

Basic Block Scheduling Example



Quiz: Shown are the register data dependence constraints.
What are the memory data dependence constraints?

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 for Basic Blocks

- **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

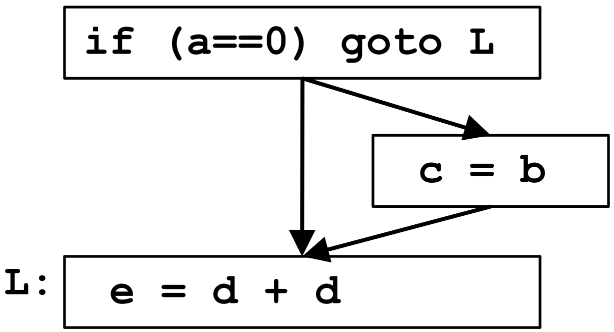
Quiz: Why use the simple list scheduling algorithm for basic blocks?

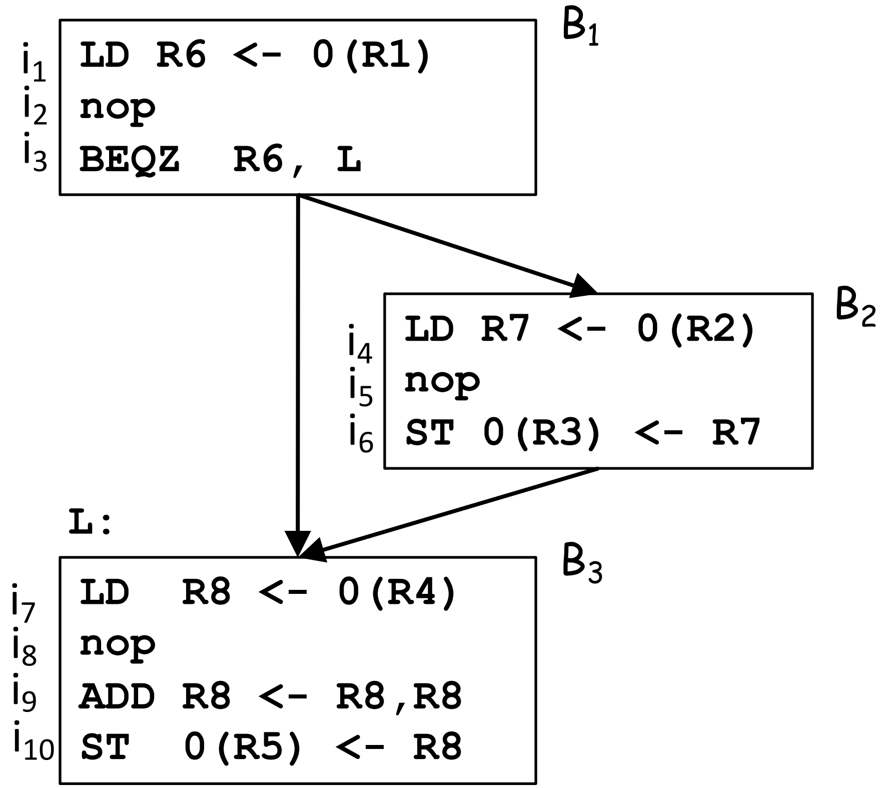
Quiz: How many operations are in a basic block?

Quiz: How much parallelism is in a basic block?

II. Introduction to Global Scheduling

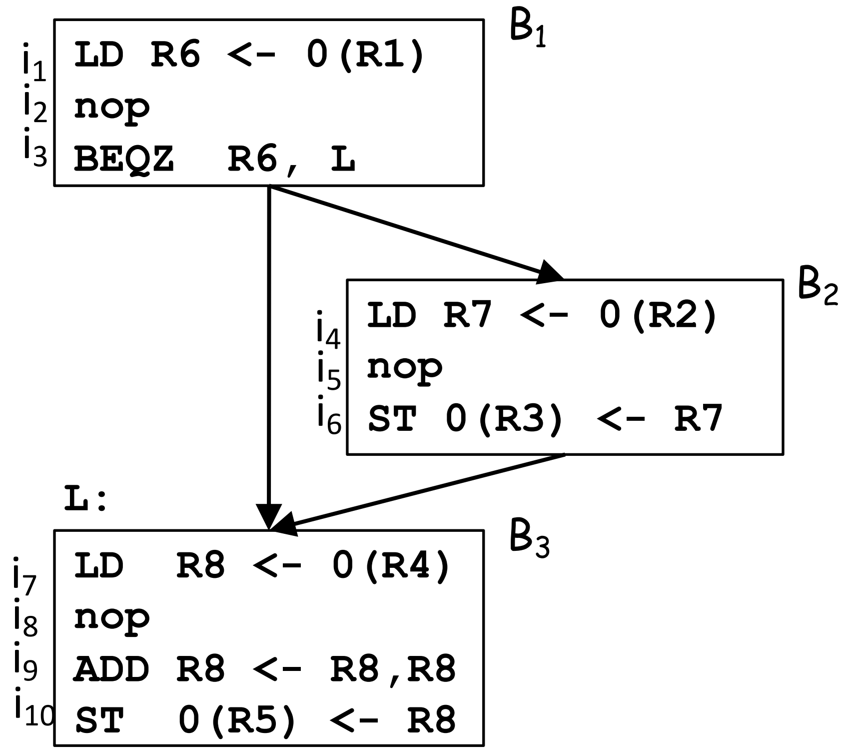
Assume each clock can execute 2 operations of any kind & no aliases

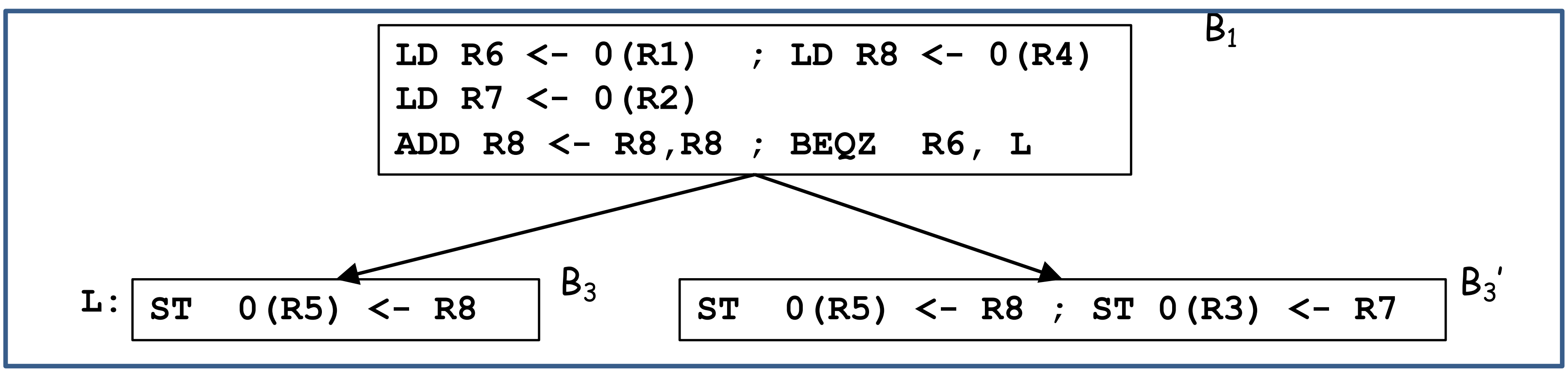




Quiz: Is there parallelism in this program? How do you schedule it?

Result of Code Scheduling

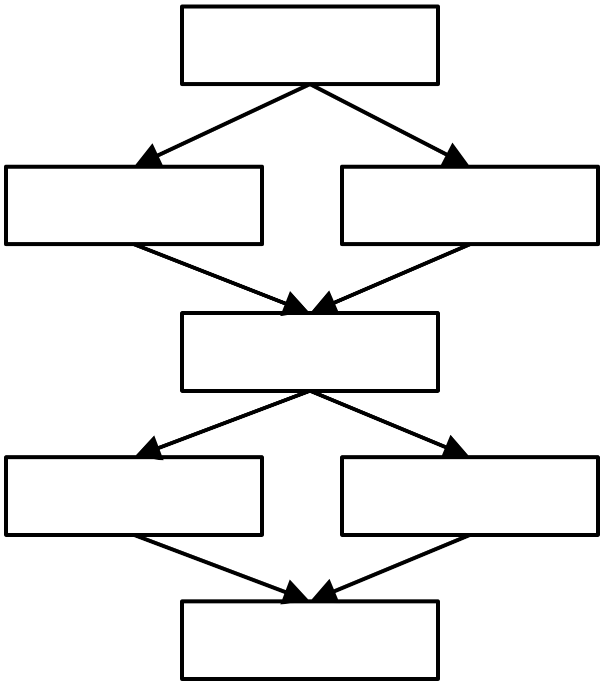




Lessons from the Example

- Basic blocks are small, lots of dependences
- Global scheduling (across basic blocks) is necessary
  - Lots of dependences esp. with memory operations (esp. due to aliases)
- Static schedulers can look ahead
  & prioritize over dynamic schedulers.

Control Dependence Constraints



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

Quiz: what are the differences between static and dynamic schedulers?

Summary

- **List scheduling**
  - Greedy algorithm with no backtracking
  - Topological sort with a priority function to choose among candidates
- **Global scheduling**
  - Limited opportunity of code motion within a single basic block
  - Concepts of control dependence, control equivalence, and speculative execution