Reading Assignment

- Read Goodman and Hsu's paper, "Code Scheduling and Register Allocation in Large Basic Blocks."
- Read Bernstein and Rodeh's paper, "Global Instruction Scheduling for Superscalar Machines." (Linked from the class Web page.)

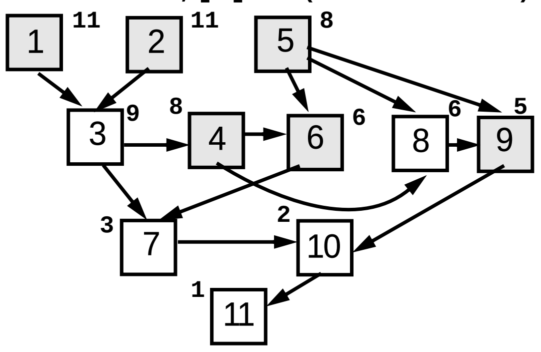
Gibbons & Muchnick Postpass Code Scheduler

1. If there is only one root, schedule it.
2. If there is more than one root, choose that root that won't be stalled by instructions already scheduled.
3. If more than one root can be scheduled without stalling, consider the following rules (in order);
   (a) Does this root stall any of its successors? (If so, schedule it immediately.)
   (b) How many new roots are exposed if this node is scheduled? (More is better.)

(c) Which root has the longest weighted path to a leaf (using instruction delays as the weight). (The "critical path" in the DAG gets priority.)

Example

```
 1.  ld    [a], %r1  //Longest path
 2.  ld    [b], %r2  //Exposes a root
 5.  ld    [d], %r3  //Not delayed
 3.  add   %r1,%r2,%r1 //Only choice
 4.  ld    [c], %r2  //Only choice
 6.  smul  %r2,%r3,%r4 //Stalls succ.
 8.  add   %r2,%r3,%r2 //Not delayed
 9.  smul  %r2,%r3,%r2 //Not delayed
 7.  add   %r1,%r4,%r1 //Only choice
10.  add   %r1,%r2,%r1 //Only choice
11.  st    %r1,[a]      (2 Stalls Total)
```



False Dependencies

We still have delays in the schedule that was produced because of “false dependencies.”

Both **b** and **c** are loaded into **%r2**. This limits the ability to move the load of **c** prior to any use of **%r2** that uses **b**.

To improve our schedule we can use a processor that renames registers *or* allocate additional registers to remove false dependencies.

Register Renaming

Many out of order processors automatically rename distinct uses of the same architectural register to distinct internal registers.

Thus

```
ld [a],%r1
ld [b],%r2
add %r1,%r2,%r1
ld [c],%r2
```

is executed as if it were

```
ld [a],%r1
ld [b],%r2
add %r1,%r2,%r3
ld [c],%r4
```

Now the final load can be executed prior to the add, eliminating a stall.

Compiler Renaming

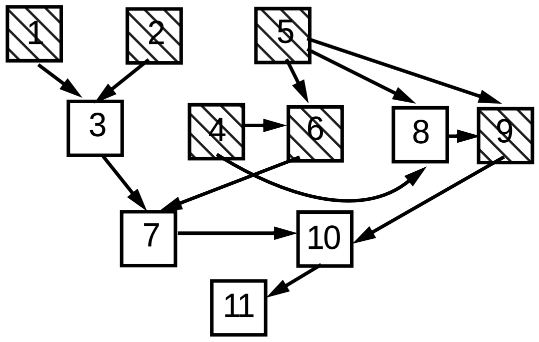
A compiler can also use the idea of renaming to avoid unnecessary stalls.

An extra register may be needed (as was the case for scheduling expression trees).

Also, a *round-robin* allocation policy is needed. Registers are reused in a *cyclic* fashion, so that the most recently freed register is reused last, not first.

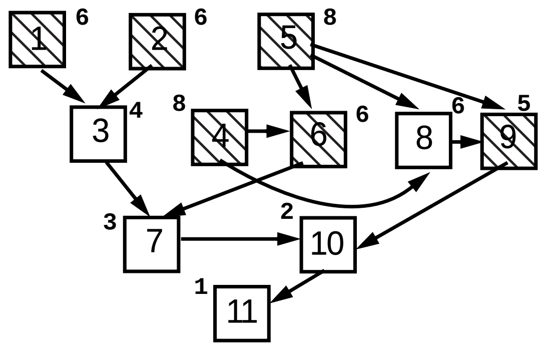
Example

```
1.  ld   [a], %r1
2.  ld   [b], %r2
3.  add  %r1,%r2,%r1   <--- Stall
4.  ld   [c], %r3
5.  ld   [d], %r4
6.  smul %r3,%r4,%r5   <--- Stall
7.  add  %r1,%r5,%r2   <--- Stall*2
8.  add  %r3,%r4,%r3
9.  smul %r3,%r4,%r3
10. add  %r2,%r3,%r2   <--- Stall*2
11. st   %r2,[a]        (6 Stalls Total)
```



After Scheduling:

```
 4.  ld    [c],%r3   //Longest path
 5.  ld    [d],%r4   //Exposes a root
 1.  ld    [a],%r1   //Stalls succ.
 2.  ld    [b],%r2   //Exposes a root
 6.  smul  %r3,%r4,%r5  //Stalls succ.
 8.  add   %r3,%r4,%r3  //Longest path
 9.  smul  %r3,%r4,%r3  //Stalls succ.
 3.  add   %r1,%r2,%r1  //Only choice
 7.  add   %r1,%r5,%r2  //Only choice
10.  add   %r2,%r3,%r2  //Only choice
11.  st    %r2,[a]      (0 Stalls Total)
```



Balanced Scheduling

When scheduling a load, we normally anticipate the *best* case, a hit in the primary cache.

On older architectures this makes sense, since we stall execution on a cache miss.

Many newer architectures are *non-blocking*. This means we can continue execution after a miss until the loaded value is used.

Assume a Cache miss takes N cycles (N is typically 10 or more).

Do we schedule a load anticipating a 1 cycle delay (a hit) or an N cycle delay (a miss)?

Neither *Optimistic Scheduling* (expect a hit) nor *Pessimistic Scheduling* (expect a miss) is *always* better.

Consider

$$\begin{tikzcd}
\text{load} \arrow[dr] & & & & \text{Inst2} \arrow[dl] \\
& \text{Inst1} \arrow[dr] & & \text{Inst3} \arrow[dl] & \\
& & \text{Inst4} & &
\end{tikzcd}$$

An Optimistic Schedule is

load Inst2 Inst1 Inst3 Inst4	Fine for a hit; inferior for a miss.

A Pessimistic Schedule is

load Inst2 Inst3 Inst1 Inst4	Fine for a hit; better for a miss.

But things become more complex with multiple loads

$$\begin{tikzcd}
\text{load1} \arrow[dr] & & & & \text{Inst1} \arrow[dl] \\
& \text{load2} \arrow[dr] & & \text{Inst2} \arrow[dl] & \\
& & \text{Inst3} & &
\end{tikzcd}$$

An Optimistic Schedule is

load1 Inst1 load2 Inst2 Inst3	Better for hits; same for misses.

A Pessimistic Schedule is

load1 Inst1 Inst2 load2 Inst3	Worse for hits; same for misses.

Balance Placement of Loads

Eggers suggests a *balanced scheduler* that spaces out loads, using available independent instructions as “filler.”

The insight is that scheduling should not be driven by worst-case latencies but rather by available *Independent* Instructions.

For

$$\begin{tikzcd} \text{load} \arrow[dr] & & & & \text{Inst2} \arrow[dl] \\ & \text{Inst1} \arrow[dr] & & \text{Inst3} \arrow[dl] & \\ & & \text{Inst4} & & \end{tikzcd}$$

it produces

load
Inst2
Inst3
Inst1
Inst4

Good; maximum distance between load and Inst1 in case of a miss.

For

$$\begin{tikzcd} \text{load1} \arrow[dr] & & & & \text{Inst1} \arrow[dl] \\ & \text{load2} \arrow[dr] & & \text{Inst2} \arrow[dl] & \\ & & \text{Inst3} & & \end{tikzcd}$$

balanced scheduling produces

load1
Inst1
load2
Inst2
Inst3

Good for hits; as good as possible for misses.

Idea of the Algorithm

Look at each Instruction, i, in the Dependency DAG.

Determine which loads can run in parallel with i and use all (or part) of i’s execution time to cover the latency of these loads.

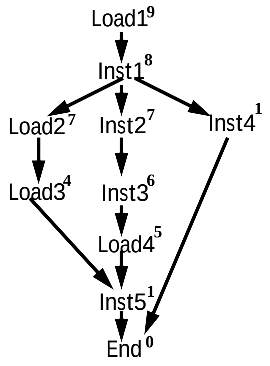
```
Compute available latency of each load:
 Give each load instruction an initial
    latency of 1.
 For (each instruction i in the
  Dependency DAG) do:
    Consider Instructions Independent
       of i:
        $G_{ind}$ = DepDAG -
          (AllPred(i) U AllSucc(i) U {i})
       For (each connected subgraph c
            in $G_{ind}$) do:
           Find m = maximum number of
               load instructions on any
               path in c.
           For (each load d in c) do:
                 add 1/m to d’s latency.
```

Computing the Schedule Using Adjusted Latencies

Once latencies are assigned to each load (other instructions have a latency of 1), we annotate each instruction in the Dependency DAG with its critical path weight: the maximum latency (along any path) from the instruction to a Leaf of the DAG.

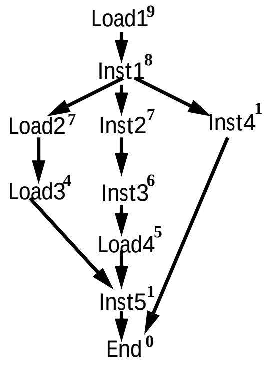
Instructions are scheduled using critical path values; the root with the highest critical path value is always scheduled next. In cases of ties (same critical path value), operations with the longest latency are scheduled first.

Example



	Ld 1	Ld 2	Ld 3	Ld 4	I1	I2	I3	I4	I5	Latency
Load1										**1+0 = 1**
Load2				**1/2**		**1/2**	**1/2**	**1/2**		**1+2 = 3**
Load3				**1/2**		**1/2**	**1/2**	**1/2**		**1+2 = 3**
Load4		**1**	**1**					**1**		**1+3 = 4**

Using the annotated Dependency Dag, instructions can be scheduled:



Load1	(0 latency; unavoidable)
Inst1	
Load2	(3 instruction latency)
Inst2	
Inst3	
Load4	(2 instruction latency)
Load3	(1 instruction latency)
Inst4	
Inst5	