Lecture 17

Intro to Instruction Scheduling

Reading: Chapter 10.1 – 10.2

Optimization: *What's the Point?* (A Quick Review)

Machine-Independent Optimizations:

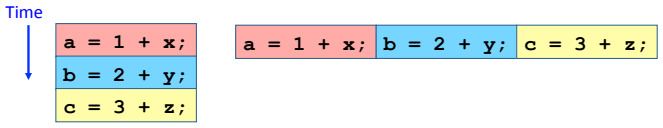
- e.g., constant propagation & folding, redundancy elimination, dead-code elimination, etc.
- Goal: *eliminate work*

Machine-Dependent Optimizations:

- register allocation
  - Goal: *reduce cost of accessing data*
- instruction scheduling
  - Goal: *???*
- …

The Goal of Instruction Scheduling

- Assume that the remaining instructions are all essential
  - (otherwise, earlier passes would have eliminated them)
- How can we perform this fixed amount of work in less time?
  - Answer: *execute the instructions in parallel*



Hardware Support for Parallel Execution

- Three forms of parallelism are found in modern machines:
  - Pipelining
  - Superscalar Processing
  - Multiprocessing

Instruction Scheduling

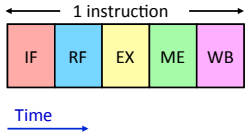
Automatic Parallelization
(covered later in class)

Pipelining

Basic idea:

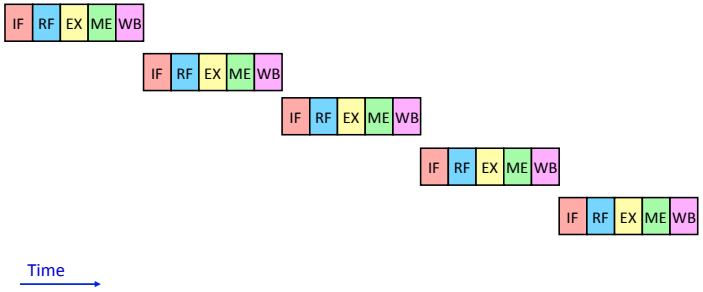
- break instruction into *stages* that can be overlapped

Example: simple 5-stage pipeline from early RISC machines

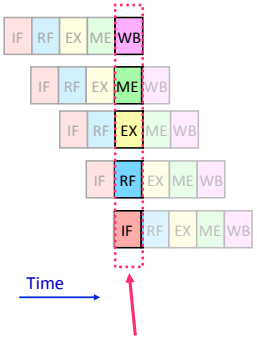


IF = Instruction Fetch
RF = Decode & Register Fetch
EX = Execute on ALU
ME = Memory Access
WB = Write Back to Register File

Pipelining Illustration



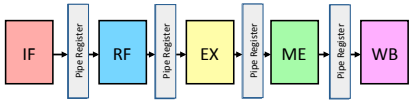
Pipelining Illustration



- In a given cycle, each instruction is in a different stage

Beyond 5-Stage Pipelines: Even More Parallelism

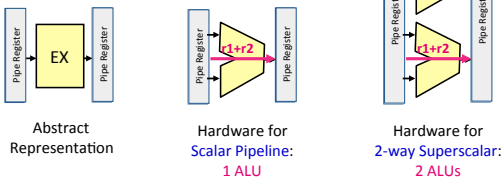
- Should we simply make pipelines deeper and deeper?



  - registers between pipeline stages have fixed overheads
    - hence diminishing returns with more stages (Amdahl's Law)
  - value of pipe stage unclear if < time for integer add
- However, many consumers think "performance = clock rate"
  - perceived need for higher clock rates -> deeper pipelines
  - e.g., Pentium 4 processor had a 20-stage pipeline

Beyond Pipelining: "Superscalar" Processing

- Basic Idea:
  - multiple (independent) instructions can proceed simultaneously through the same pipeline stages
- Requires additional hardware
  - example: "Execute" stage

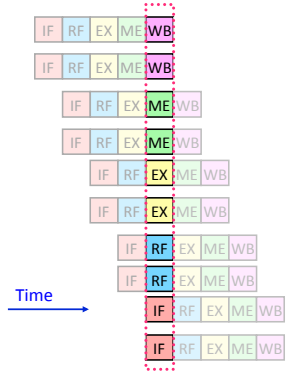


Abstract Representation

Hardware for Scalar Pipeline: 1 ALU

Hardware for 2-way Superscalar: 2 ALUs

Superscalar Pipeline Illustration



Original (scalar) pipeline:

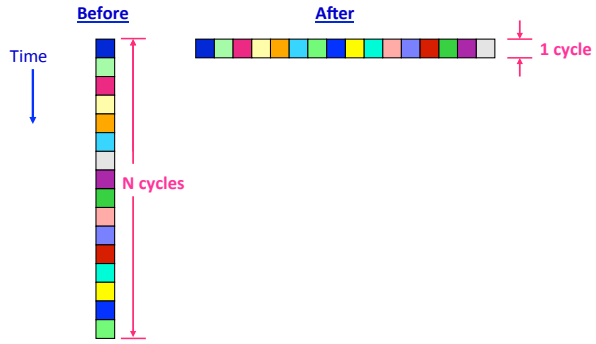
- Only one instruction in a given pipe stage at a given time

Superscalar pipeline:

- Multiple instructions in the same pipe stage at the same time

The Ideal Scheduling Outcome

- What prevents us from achieving this ideal?



Limitations Upon Scheduling

1. Hardware Resources
2. Data Dependences
3. Control Dependences

Limitation #1: Hardware Resources

- Processors have finite resources, and there are often constraints on how these resources can be used.

Examples:

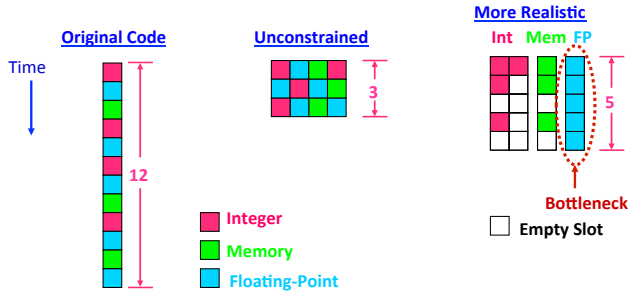
- Finite issue width
- Limited functional units (FUs) per given instruction type
- Limited pipelining within a given functional unit (FU)

Finite Issue Width

- Prior to superscalar processing:
  - processors only "issued" one instruction per cycle
- Even with superscalar processing:
  - limit on total # of instructions issued per cycle

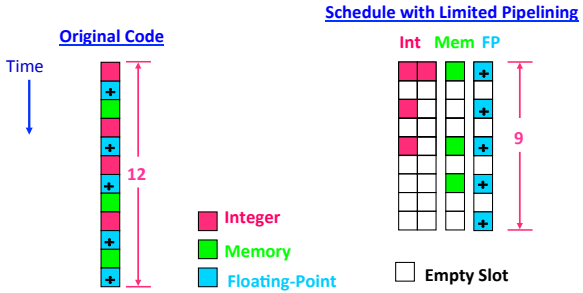
Limited FUs per Instruction Type

- e.g., a 4-way superscalar might only be able to issue up to 2 integer, 1 memory, and 1 floating-point insts per cycle



Limited Pipelining within a Functional Unit

- e.g., only 1 new floating-point division once every 2 cycles



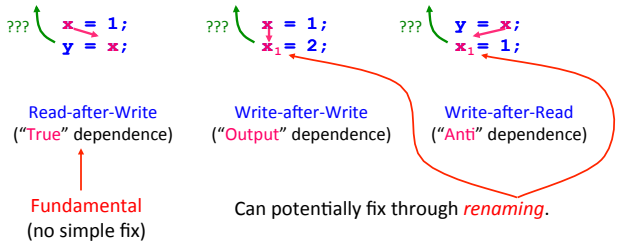
Limitations Upon Scheduling

1. Hardware Resources
2. Data Dependences
3. Control Dependences

Limitation #2: Data Dependences

- If we read or write a data location "too early", the program may behave incorrectly.

(Assume that initially, `x = 0`.)



Why Data Dependences are Challenging

```
x = a[i];
*p = 1;
 y = *q;
*r = z;
```

- which of these instructions can be reordered?
- *ambiguous data dependences* are very common in practice
  - difficult to resolve, despite fancy pointer analysis

Given Ambiguous Data Dependences, What To Do?

```
x = a[i];
*p = 1;
 y = *q;
*r = z;
```

- Conservative approach: don't reorder instructions
  - ensures correct execution
  - but may suffer poor performance
- Aggressive approach?
  - is there a way to safely reorder instructions?

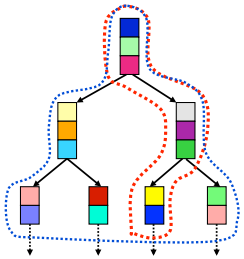
Hardware Limitations: Multi-cycle Execution Latencies

- Simple instructions often "execute" in one cycle
  - (as observed by other instructions in the pipeline)
  - e.g., integer addition
- More complex instructions may require multiple cycles
  - e.g., integer division, square-root
  - cache misses!
- These latencies, when combined with data dependencies, can result in non-trivial critical path lengths through code

Limitations Upon Scheduling

1. Hardware Resources
2. Data Dependences
3. Control Dependences

Limitation #3: Control Dependences



- What do we do when we reach a conditional branch?
  - choose a "frequently-executed" path?
  - choose multiple paths?

Scheduling Constraints: Summary

- 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

Hardware- vs. Compiler-Based Scheduling

- The hardware can also attempt to reschedule instructions (on-the-fly) to improve performance
- What advantages/disadvantages would hardware have (vs. the compiler) when trying to reason about:
  - Hardware Resources
  - Data Dependences
  - Control Dependences
- Which is better:
  - doing more of the scheduling work in the compiler?
  - doing more of the scheduling work in the hardware?

Spectrum of Hardware Support for Scheduling

Compiler-Centric ⟷ Hardware-Centric

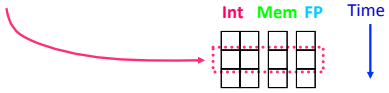
VLIW *(Very Long Instruction Word)*	**In-Order Superscalar**	**Out-of-Order Superscalar**
e.g.: Itanium	e.g.: Original Pentium	e.g.: Pentium 4

VLIW Processors

Motivation:
- if the hardware spends zero (or almost zero) time thinking about scheduling, it can run faster

Philosophy:
- give full control over scheduling to the compiler

Implementation:
- expose control over all FUs directly to software via a *"very long instruction word"*



Compiling for VLIW

Predicting Execution Latencies:
- easy for most functional units (latency is fixed)
- but what about memory references?

Data Dependences:
- in "pure" VLIW, the hardware does not check for them
  - the compiler takes them into account to produce safe code

```
a = b + 1;
c = a - d;
e = c / 3;
f = g - e;
```

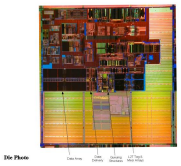
Example #1

```
while (p != NULL) {
  if (test(p->val))
    q->next = p->left;
  p = p->next;
}
```

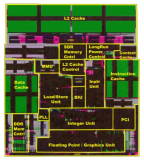
Example #2

"VLIW" Today

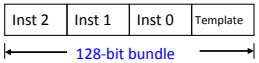
- Hardware checks for data dependences through memory
- Compiler can do a good job with register dependences



Intel/HP Itanium2



Transmeta Crusoe 5400



- Runtime software dynamically generates VLIW code

Spectrum of Hardware Support for Scheduling

In-Order Superscalar Processors

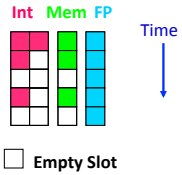
In contrast with VLIW:

- hardware does full data dependence checking
- hence, no need to encode NOPs for empty slots

- Once an instruction cannot be issued, no instructions after it will be issued.

Bottom Line:

- hardware matches code to available resources; recompilation is not necessary for correctness
- compiler's role is still important
  - for performance, not correctness!



Spectrum of Hardware Support for Scheduling

Out-of-Order Superscalar Processors

Motivation:

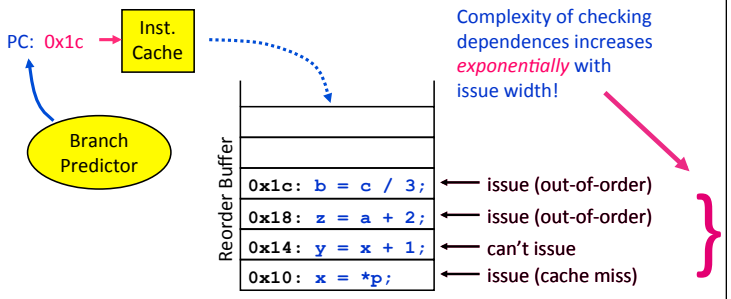
- when an instruction is stuck, perhaps there are subsequent instructions that can be executed

```
x = *p;      ← suffers expensive cache miss
y = x + 1;   ← stuck waiting on true dependence
z = a + 2;   } ← these do not need to wait
b = c / 3;   }
```

Sounds great! But how does this complicate the hardware?

Out-of-Order Superscalar Processors: Hardware Overview

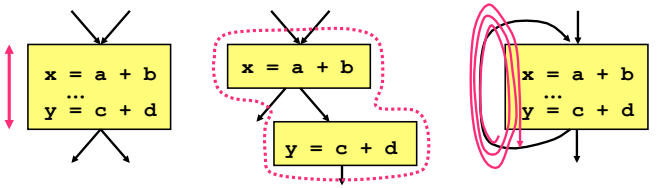
- fetch & graduate in-order, issue out-of-order



Compiler- vs. Hardware-Centric Scheduling: Bottom Line

- High-end processors will probably remain out-of-order
  - moving instructions small distances is probably useless
  - BUT, moving instructions *large* distances may still help
- Cheap, power-efficient processors may be in-order/VLIW
  - instruction scheduling may have a large impact

Scheduling Roadmap



List Scheduling:
- *within* a basic block

Global Scheduling:
- *across* basic blocks

Software Pipelining:
- *across* loop iterations