

# CS 152 Computer Architecture and Engineering

## CS252 Graduate Computer Architecture

### Lecture 13 –VLIW

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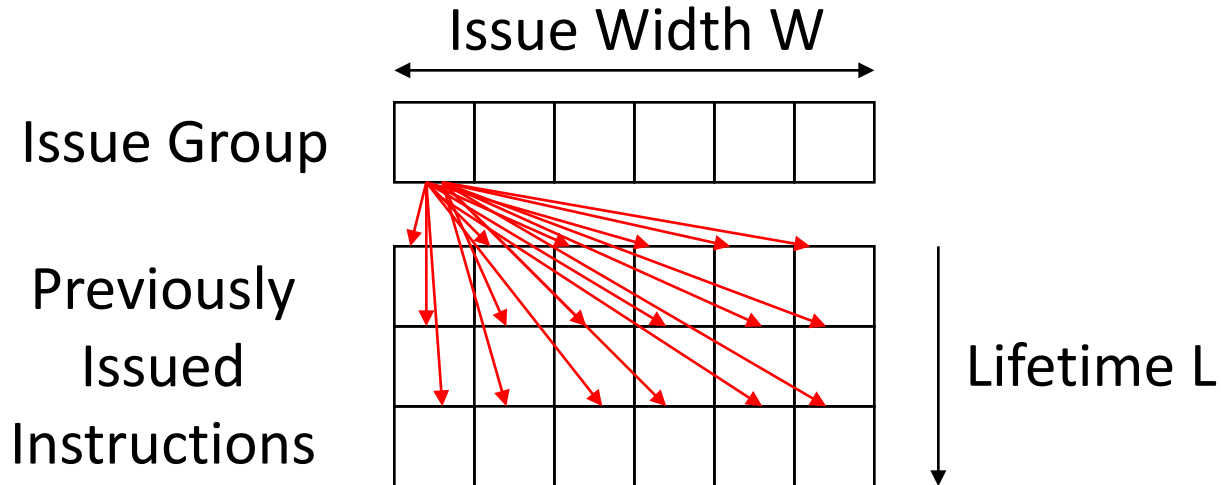
Electrical Engineering and Computer Sciences  
University of California at Berkeley

**`http://www.eecs.berkeley.edu/~krste`**  
**`http://inst.eecs.berkeley.edu/~cs152`**

# Last Time in Lecture 12

- Branch prediction
  - temporal, history of a single branch
  - spatial, based on path through multiple branches
- Branch History Table (BHT) vs. Branch History Buffer (BTB)
  - tradeoff in capacity versus latency
- Return-Address Stack (RAS)
  - specialized structure to predict subroutine return addresses
- Fetching more than one basic block per cycle
  - predicting multiple branches
  - trace cache

# Superscalar Control Logic Scaling

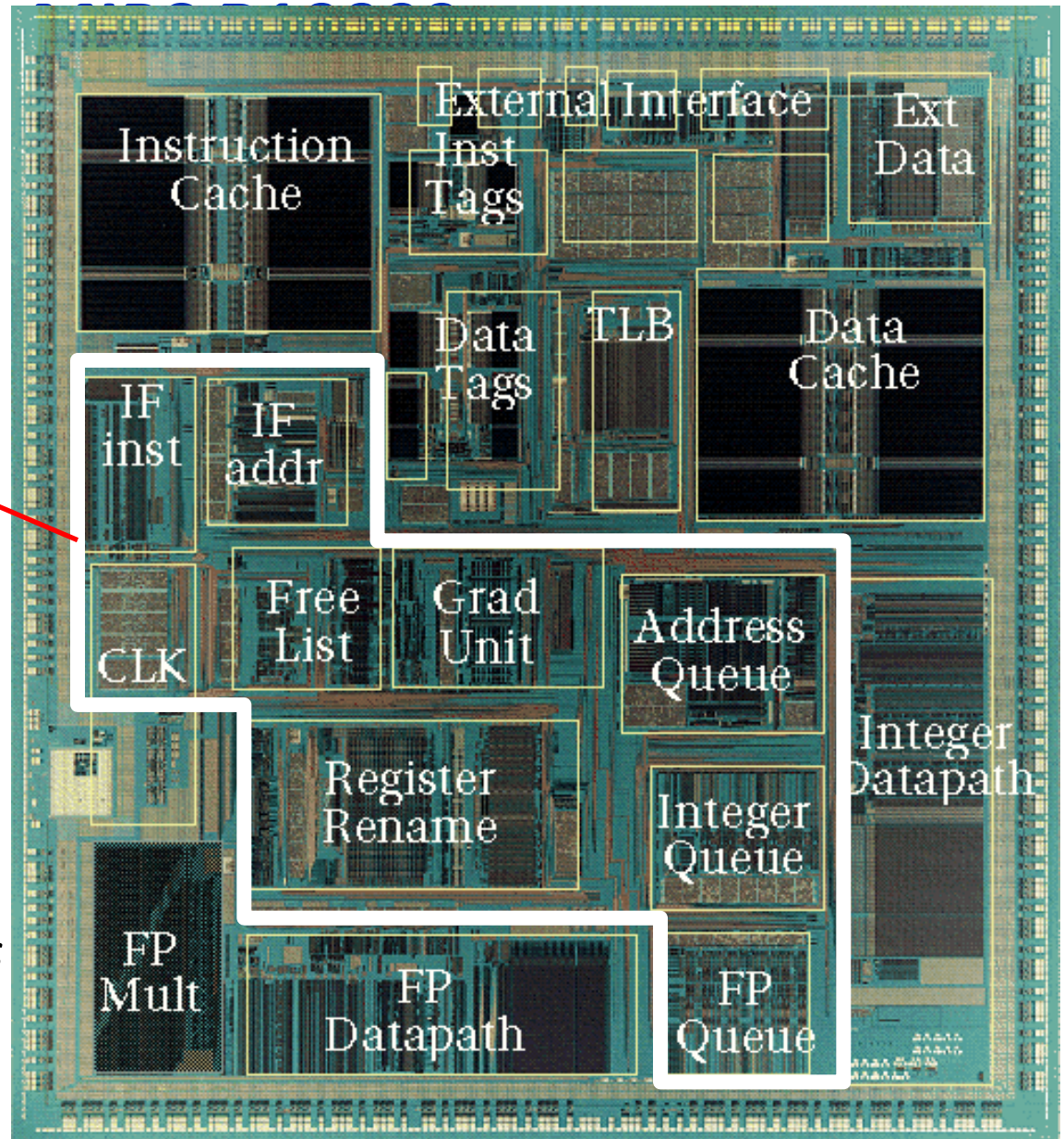


- Each issued instruction must somehow check against  $W \cdot L$  instructions, i.e., growth in hardware  $\propto W \cdot (W \cdot L)$
- For in-order machines,  $L$  is related to pipeline latencies and check is done during issue (interlocks or scoreboard)
- For out-of-order machines,  $L$  also includes time spent in instruction buffers (instruction window or ROB), and check is done by broadcasting tags to waiting instructions at write back (completion)
- As  $W$  increases, larger instruction window is needed to find enough parallelism to keep machine busy  $\Rightarrow$  greater  $L$

*$\Rightarrow$  Out-of-order control logic grows faster than  $W^2$  ( $\sim W^3$ )*

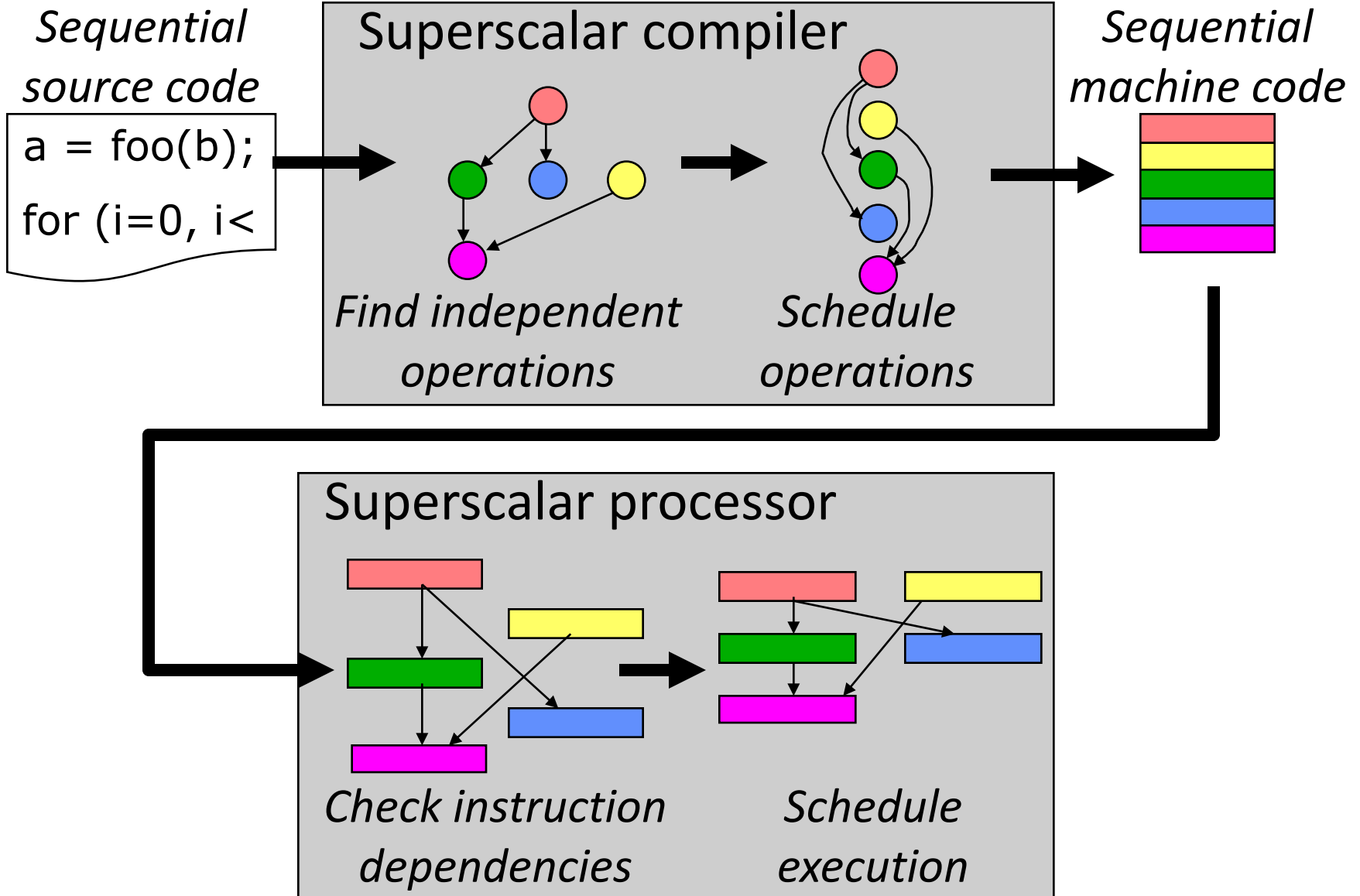
# Out-of-Order Control Complexity:

*Control  
Logic*

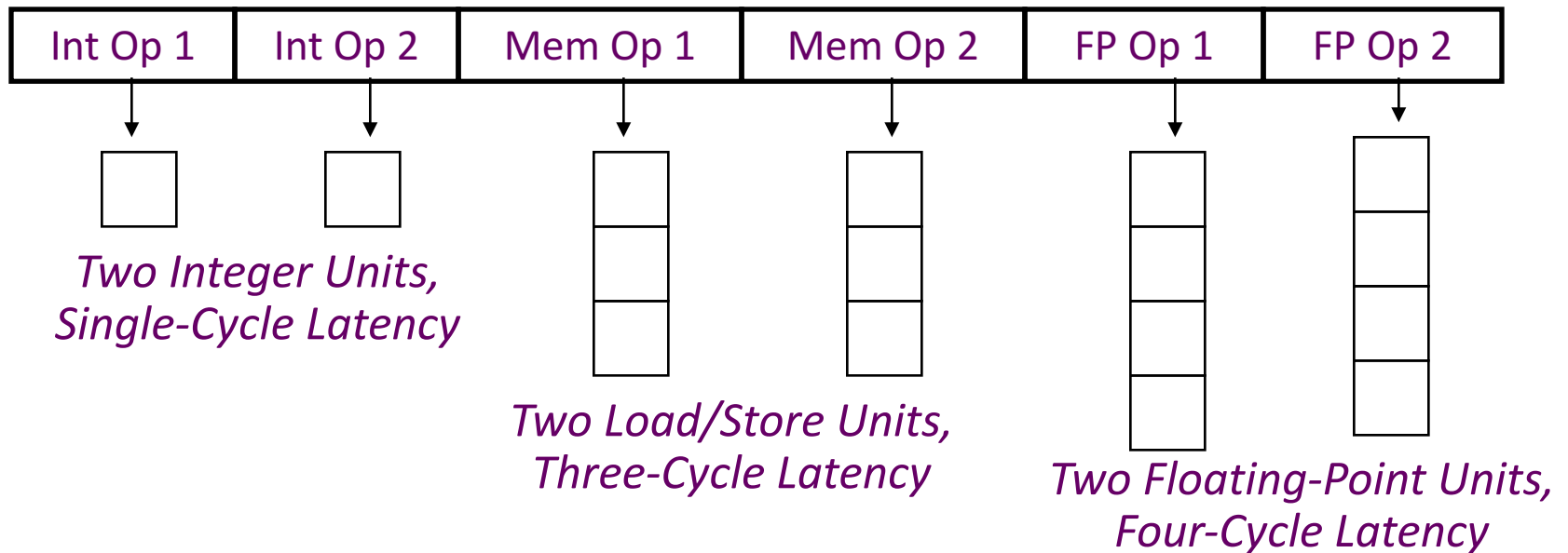


*[ SGI/MIPS Technologies  
Inc., 1995 ]*

# Sequential ISA Bottleneck



# VLIW: Very Long Instruction Word



- Multiple operations packed into one instruction
- Each operation slot is for a fixed function
- Constant operation latencies are specified
- Architecture requires guarantee of:
  - Parallelism within an instruction => no cross-operation RAW check
  - No data use before data ready => no data interlocks

# Early VLIW Machines

- **FPS AP120B (1976)**
  - scientific attached array processor
  - first commercial wide instruction machine
  - hand-coded vector math libraries using software pipelining and loop unrolling
- **Multiflow Trace (1987)**
  - commercialization of ideas from Fisher's Yale group including "trace scheduling"
  - available in configurations with 7, 14, or 28 operations/instruction
  - 28 operations packed into a 1024-bit instruction word
- **Cydrome Cydra-5 (1987)**
  - 7 operations encoded in 256-bit instruction word
  - rotating register file

# VLIW Compiler Responsibilities

- Schedule operations to maximize parallel execution
- Guarantees intra-instruction parallelism
- Schedule to avoid data hazards (no interlocks)
  - Typically separates operations with explicit NOPs



# Loop Execution

```
for (i=0; i<N; i++)
    B[i] = A[i] + C;
```

↓ *Compile*

```
loop: fld f1, 0(x1)
      add x1, 8
      fadd f2, f0, f1
      fsd f2, 0(x2)
      add x2, 8
      bne x1, x3,
loop
```

→ *Schedule*

	Int1	Int 2	M1	M2	FP+	FPx
loop:	add x1		fld			
					fadd	
	add x2	bne	fsd			

How many FP ops/cycle?

1 fadd / 8 cycles = 0.125

# Loop Unrolling

```
for (i=0; i<N; i++)  
    B[i] = A[i] + C;
```

Unroll inner loop to perform 4 iterations at once

```
for (i=0; i<N; i+=4)  
{  
    B[i]    = A[i] + C;  
    B[i+1] = A[i+1] + C;  
    B[i+2] = A[i+2] + C;  
    B[i+3] = A[i+3] + C;  
}
```

Need to handle values of N that are not multiples of unrolling factor with final cleanup loop

# Scheduling Loop Unrolled Code

*Unroll 4 ways*

```

loop: fld f1, 0(x1)
      fld f2, 8(x1)
      fld f3, 16(x1)
      fld f4, 24(x1)
      add x1, 32
      fadd f5, f0, f1
      fadd f6, f0, f2
      fadd f7, f0, f3
      fadd f8, f0, f4
      fsd f5, 0(x2)
      fsd f6, 8(x2)
      fsd f7, 16(x2)
      fsd f8, 24(x2)
      add x2, 32
      bne x1, x3, loop
    
```

loop:  
*Schedule* →

Int1	Int 2	M1	M2	FP+	FPx
		fld f1			
		fld f2			
		fld f3			
add x1		fld f4		fadd f5	
				fadd f6	
				fadd f7	
				fadd f8	
		fsd f5			
		fsd f6			
		fsd f7			
add x2	bne	fsd f8			

How many FLOPS/cycle?

4 fadds / 11 cycles = 0.36

# Software Pipelining

Unroll 4 ways first

```

loop: fld f1, 0(x1)
      fld f2, 8(x1)
      fld f3, 16(x1)
      fld f4, 24(x1)
      add x1, 32
      fadd f5, f0, f1
      fadd f6, f0, f2
      fadd f7, f0, f3
      fadd f8, f0, f4
      fsd f5, 0(x2)
      fsd f6, 8(x2)
      fsd f7, 16(x2)
      fsd f8, -8(x2)
      add x2, 32
      fsd f8, -8(x2)
      bne x1, x3, loop
    
```

Int1	Int 2	M1	M2	FP+	FPx
		fld f1			
		fld f2			
		fld f3			
add x1		fld f4			
		fld f1		fadd f5	
		fld f2		fadd f6	
		fld f3		fadd f7	
add x1		fld f4		fadd f8	
		fld f1	fsd f5	fadd f5	
		fld f2	fsd f6	fadd f6	
	add x2	fld f3	fsd f7	fadd f7	
add x1 bne		fld f4	fsd f8	fadd f8	
			fsd f5	fadd f5	
			fsd f6	fadd f6	
	add x2		fsd f7	fadd f7	
	bne		fsd f8	fadd f8	
			fsd f5		

prolog

iterate

loop:

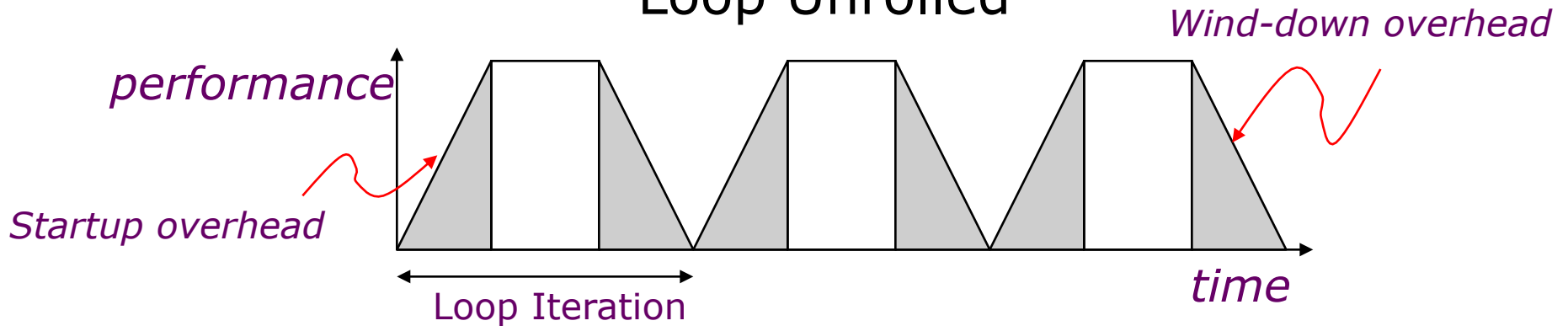
epilog

How many FLOPS/cycle?

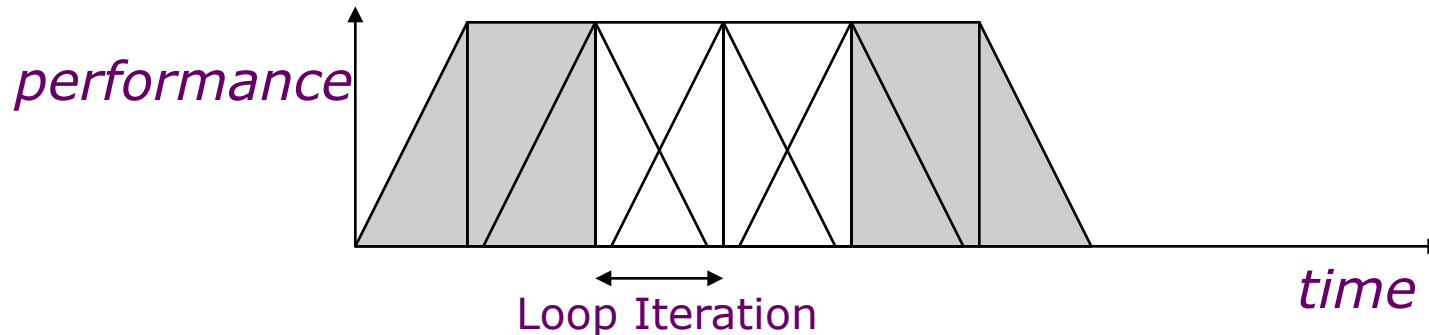
4 fadds / 4 cycles = 1

# Software Pipelining vs. Loop Unrolling

## Loop Unrolled



## Software Pipelined



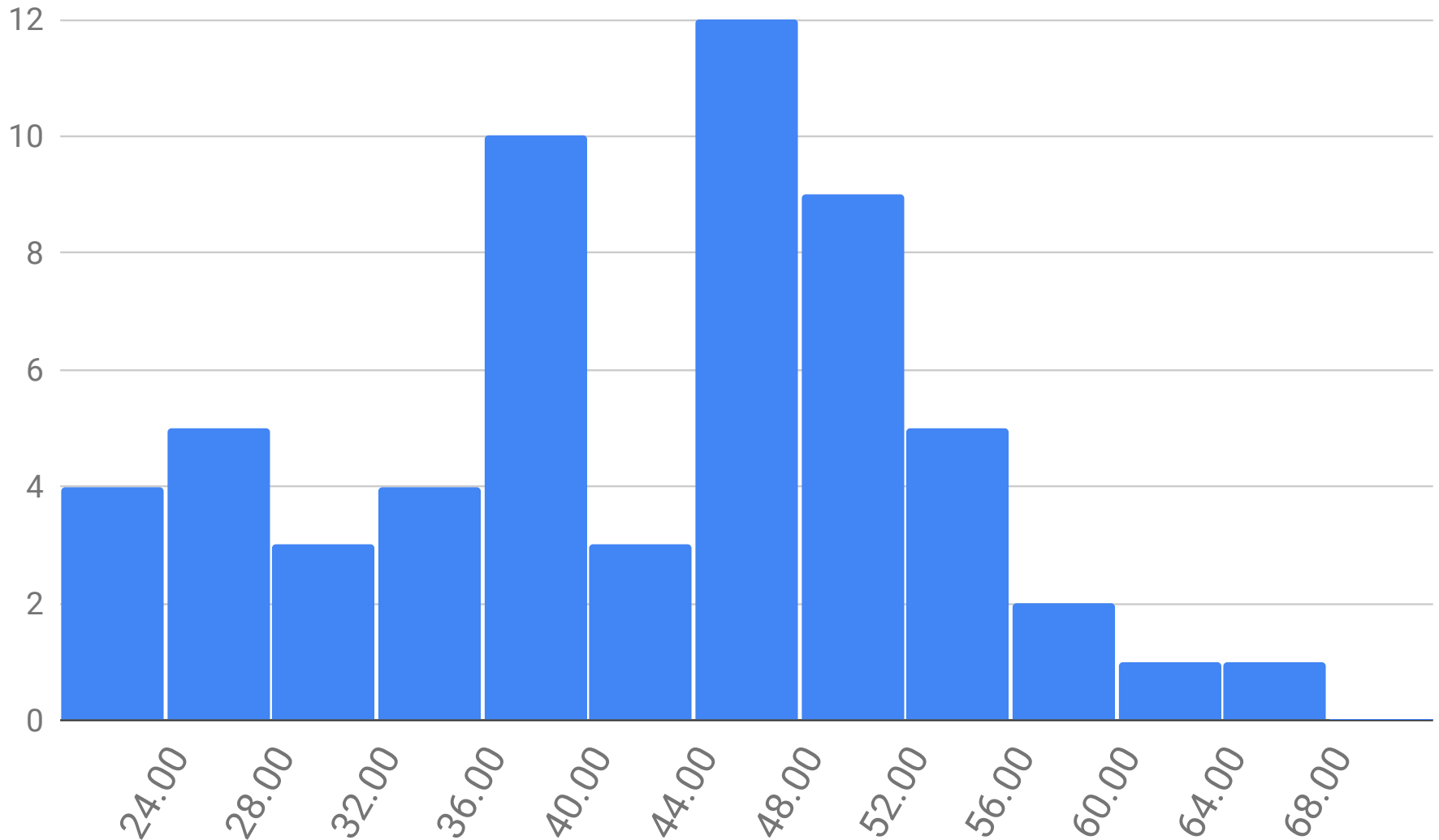
*Software pipelining pays startup/wind-down costs only once per loop, not once per iteration*

# CS152 Administrivia

- Lab 2 extension, due Friday March 15
- PS 3 due Monday March 18
- Midterm grades will be released today
- Regrade requests will be through Gradescope
  - Window opens Friday, 3/15/19 at 4pm (after section)
  - Window closes Friday, 3/22/19 at 12pm (before section)

# CS152 Administrivia

Midterm 1 Grades: mean = 41.4,  $\sigma = 11.3$

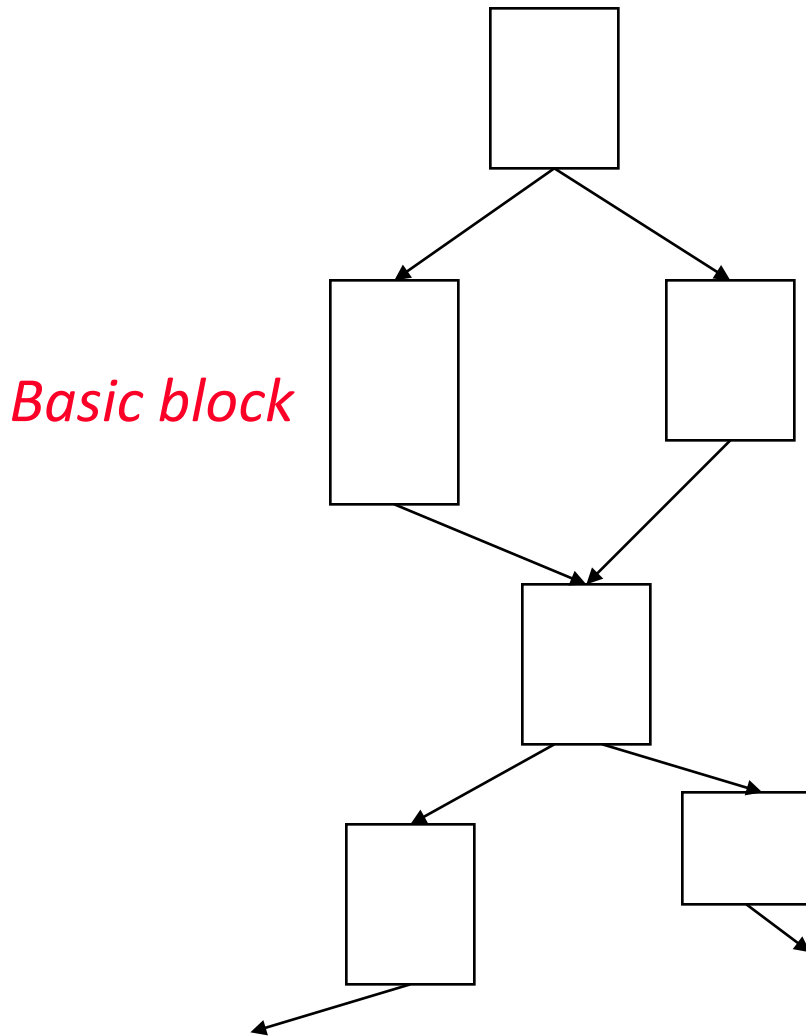


# CS252 Administrivia

- Readings next week on OoO superscalar microprocessors

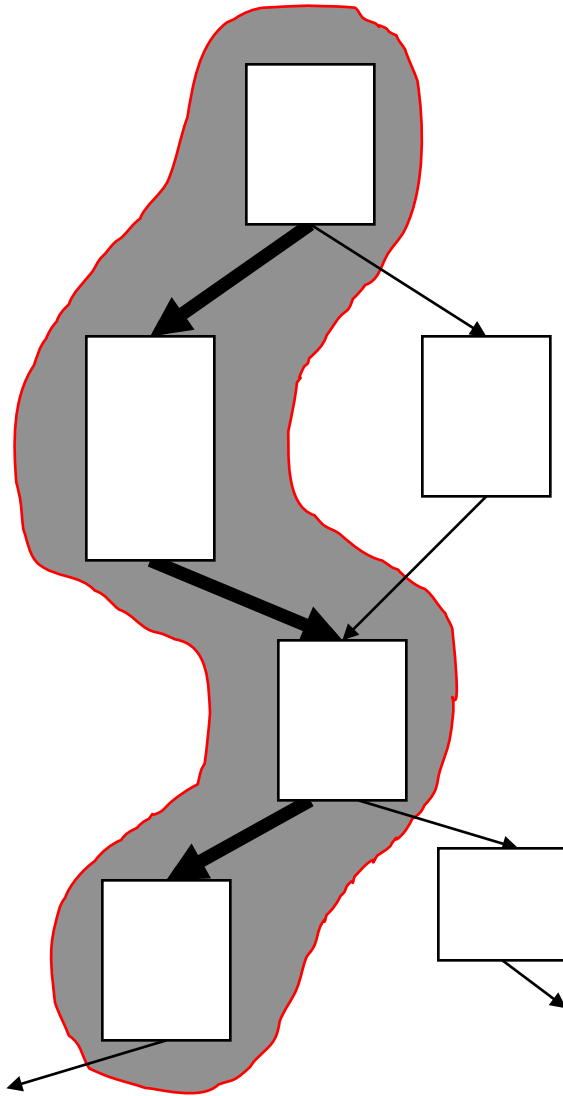


# What if there are no loops?



- Branches limit basic block size in control-flow intensive irregular code
- Difficult to find ILP in individual basic blocks

# Trace Scheduling [Fisher, Ellis]

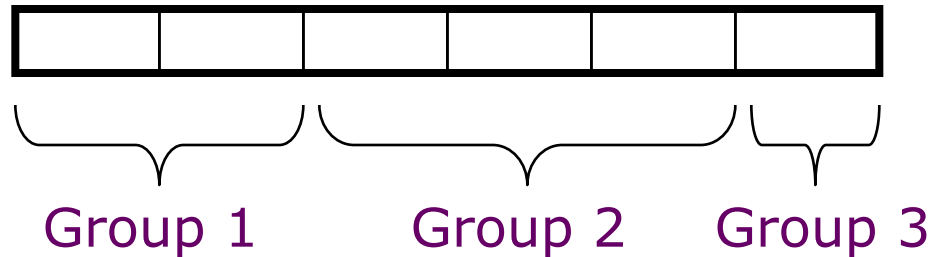


- Pick string of basic blocks, a *trace*, that represents most frequent branch path
- Use profiling feedback or compiler heuristics to find common branch paths
- Schedule whole “trace” at once
- Add fixup code to cope with branches jumping out of trace

# Problems with “Classic” VLIW

- Object-code compatibility
  - have to recompile all code for every machine, even for two machines in same generation
- Object code size
  - instruction padding wastes instruction memory/cache
  - loop unrolling/software pipelining replicates code
- Scheduling variable latency memory operations
  - caches and/or memory bank conflicts impose statically unpredictable variability
- Knowing branch probabilities
  - Profiling requires an significant extra step in build process
- Scheduling for statically unpredictable branches
  - optimal schedule varies with branch path

# VLIW Instruction Encoding

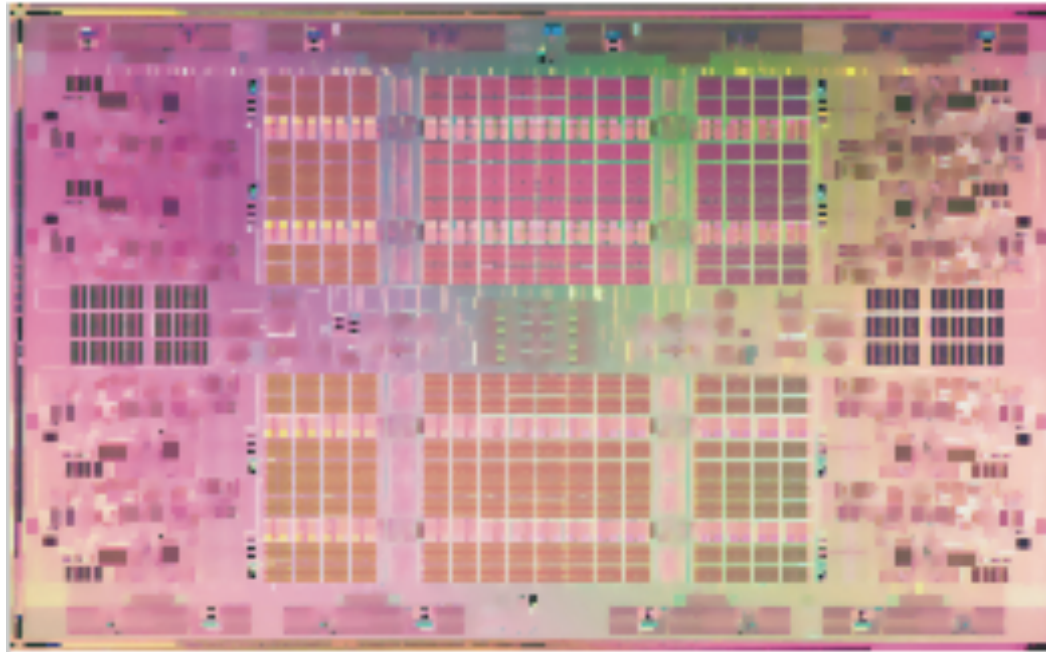


- Schemes to reduce effect of unused fields
  - Compressed format in memory, expand on I-cache refill
    - used in Multiflow Trace
    - introduces instruction addressing challenge
  - Mark parallel groups
    - used in TMS320C6x DSPs, Intel IA-64
  - Provide a single-op VLIW instruction
    - Cydra-5 UniOp instructions

# Intel Itanium, EPIC IA-64

- EPIC is the style of architecture (cf. CISC, RISC)
  - Explicitly Parallel Instruction Computing (really just VLIW)
- IA-64 is Intel's chosen ISA (cf. x86, MIPS)
  - IA-64 = Intel Architecture 64-bit
  - An object-code-compatible VLIW
- Merced was first Itanium implementation (cf. 8086)
  - First customer shipment expected 1997 (actually 2001)
  - McKinley, second implementation shipped in 2002
  - Recent version, Poulson, eight cores, 32nm, announced 2011

# Eight Core Itanium “Poulson” *[Intel 2011]*



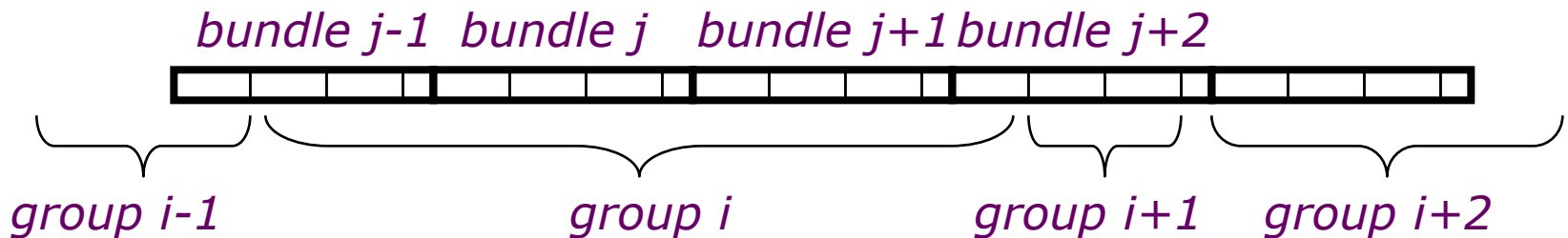
- 8 cores
- 1-cycle 16KB L1 I&D caches
- 9-cycle 512KB L2 I-cache
- 8-cycle 256KB L2 D-cache
- 32 MB shared L3 cache
- 544mm<sup>2</sup> in 32nm CMOS
- Over 3 billion transistors
- Cores are 2-way multithreaded
- 6 instruction/cycle fetch
  - Two 128-bit bundles
- Up to 12 insts/cycle execute

# IA-64 Instruction Format



128-bit instruction bundle

- Template bits describe grouping of these instructions with others in adjacent bundles
- Each group contains instructions that can execute in parallel



# IA-64 Registers

- 128 General Purpose 64-bit Integer Registers
- 128 General Purpose 64/80-bit Floating Point Registers
- 64 1-bit Predicate Registers
  
- GPRs “rotate” to reduce code size for software pipelined loops
  - Rotation is a simple form of register renaming allowing one instruction to address different physical registers on each iteration

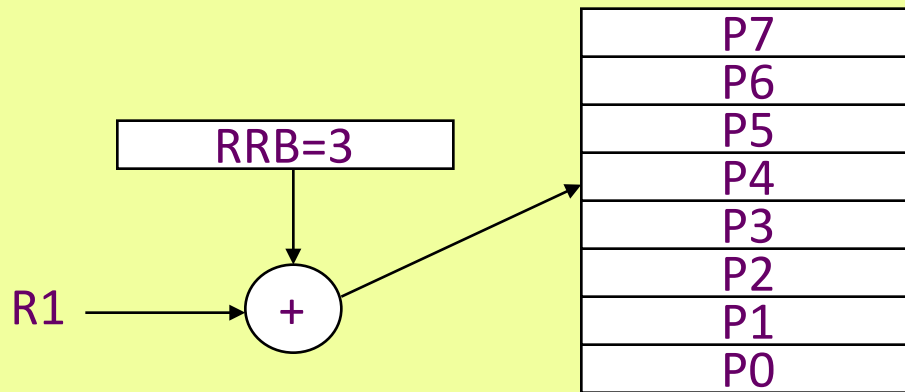


# Rotating Register Files

Problems: Scheduled loops require lots of registers,  
Lots of duplicated code in prolog, epilog

Solution: Allocate new set of registers for each loop iteration

# Rotating Register File



Rotating Register Base (RRB) register points to base of current register set. Value added on to logical register specifier to give physical register number. Usually, split into rotating and non-rotating registers.

# Rotating Register File (Previous Loop Example)

Three cycle load latency  
encoded as difference of 3  
in register specifier  
number ( $f4 - f1 = 3$ )

Four cycle fadd latency  
encoded as difference of 4  
in register specifier  
number ( $f9 - f5 = 4$ )

ld f1, ()	fadd f5, f4, ...	sd f9, ()	bloop
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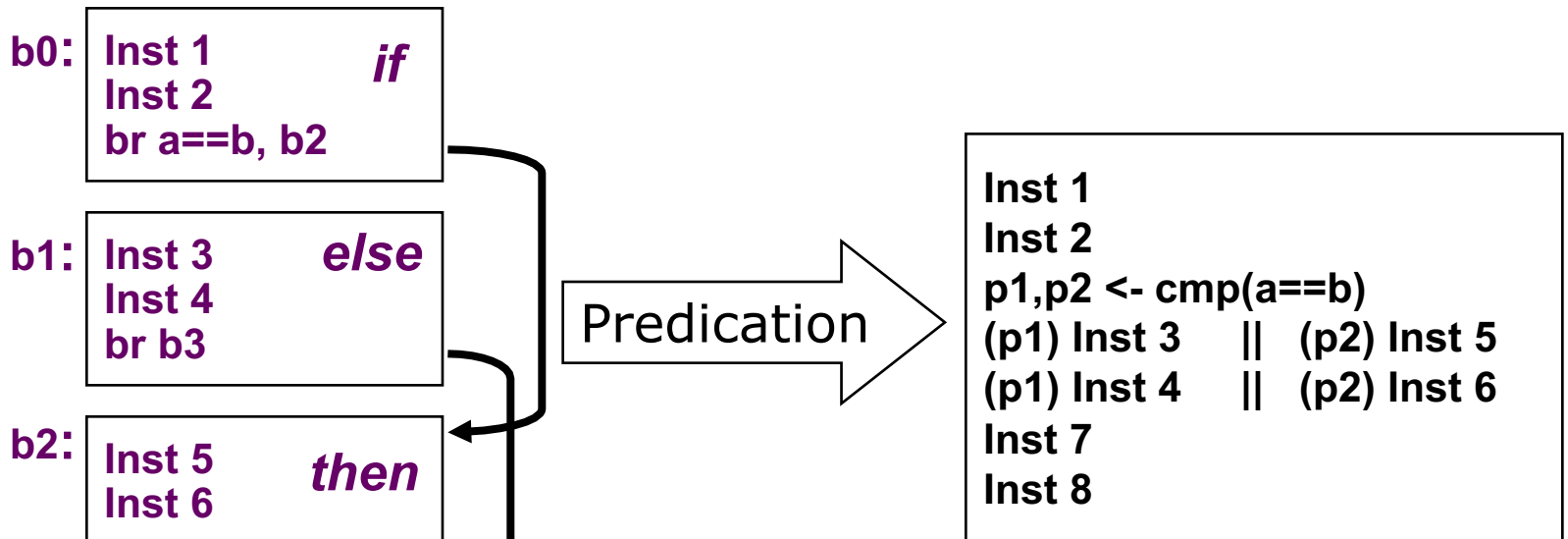
ld P9, ()	fadd P13, P12,	sd P17, ()	bloop	RRB=8
ld P8, ()	fadd P12, P11,	sd P16, ()	bloop	RRB=7
ld P7, ()	fadd P11, P10,	sd P15, ()	bloop	RRB=6
ld P6, ()	fadd P10, P9,	sd P14, ()	bloop	RRB=5
ld P5, ()	fadd P9, P8,	sd P13, ()	bloop	RRB=4
ld P4, ()	fadd P8, P7,	sd P12, ()	bloop	RRB=3
ld P3, ()	fadd P7, P6,	sd P11, ()	bloop	RRB=2
ld P2, ()	fadd P6, P5,	sd P10, ()	bloop	RRB=1

# IA-64 Predicated Execution

**Problem:** Mispredicted branches limit ILP

**Solution:** Eliminate hard to predict branches with predicated execution

- Almost all IA-64 instructions can be executed conditionally under predicate
- Instruction becomes NOP if predicate register false



One basic block

*Mahlke et al, ISCA95: On average  
>50% branches removed*

Four basic blocks

**Warning: Complicates bypassing!**

# IA-64 Speculative Execution

**Problem:** Branches restrict compiler code motion

**Solution:** Speculative operations that don't cause exceptions

Inst 1  
Inst 2  
br a==b, b2

Load r1  
Use r1  
Inst 3

*Can't move load above branch because might cause spurious exception*

Load.s r1  
Inst 1  
Inst 2  
br a==b, b2

*Speculative load never causes exception, but sets "poison" bit on destination register*

Chk.s r1  
Use r1  
Inst 3

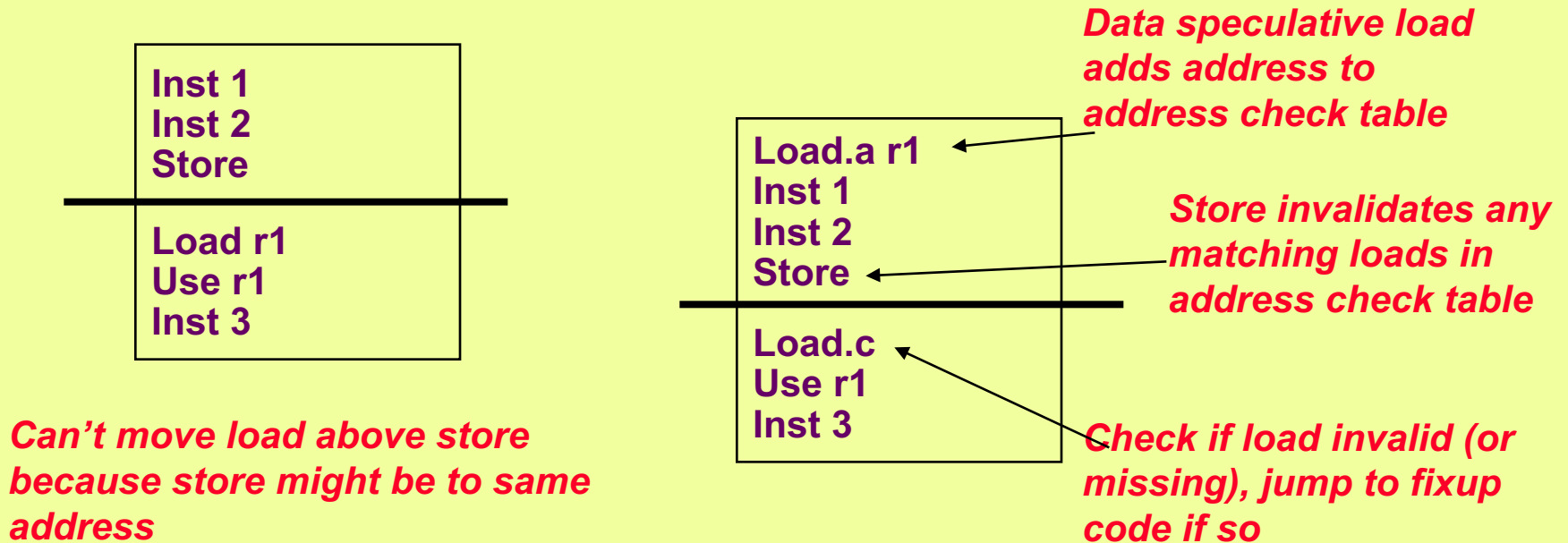
*Check for exception in original home block jumps to fixup code if exception detected*

Particularly useful for scheduling long latency loads early

# IA-64 Data Speculation

**Problem:** Possible memory hazards limit code scheduling

**Solution:** Hardware to check pointer hazards



Requires associative hardware in address check table

# Limits of Static Scheduling

- Unpredictable branches
- Variable memory latency (unpredictable cache misses)
- Code size explosion
- Compiler complexity
- Despite several attempts, VLIW has failed in general-purpose computing arena (so far).
  - More complex VLIW architectures are close to in-order superscalar in complexity, no real advantage on large complex apps.
- Successful in embedded DSP market
  - Simpler VLIWs with more constrained environment, friendlier code.

# Intel Kills Itanium

- Donald Knuth “ ... *Itanium approach that was supposed to be so terrific—until it turned out that the wished-for compilers were basically impossible to write.*”
- “*Intel officially announced the end of life and product discontinuance of the Itanium CPU family on January 30th, 2019*”, Wikipedia



# Acknowledgements

- This course is partly inspired by previous MIT 6.823 and Berkeley CS252 computer architecture courses created by my collaborators and colleagues:
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  - David Patterson (UCB)